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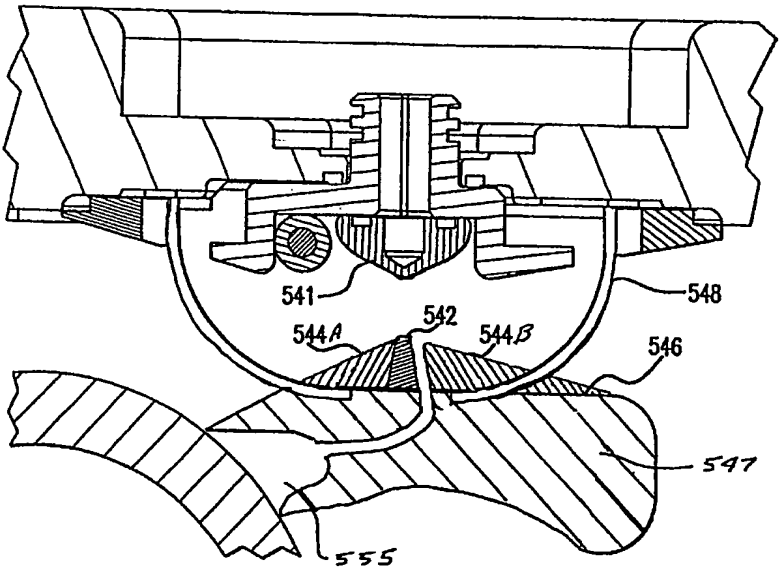
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(54) Title: SIX TO TEN KHz, OR GREATER GAS DISCHARGE LASER SYSTEM

(57) Abstract: The present invention provides gas discharge laser systems capable of reliable long-term operation in a production line capacity at repetition rates in the range of 6,000 to 10,000 pulses per second. Preferred embodiments are configured as KrF, ArF and F_2 lasers used in photolithography. Improvements include a suction fan (555) in the immediate vicinity of the anode (542) to increase gas flow. The intake of the fan (555) is between the anode (542) and the insulating spacer (544B).

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SIX TO TEN KHz, OR GREATER GAS DISCHARGE LASER SYSTEM

The present invention claims priority to Serial No. 10/187,336 filed June 28, 2002, Serial No. 10/141,216 filed May 7, 2002, Serial No. 10/036,676 filed December 21, 2001, Serial No. 10/012,002, filed November 30, 2001, Serial No. 10/029,319, filed October 17, 2001, 09/943,343, filed August 29, 2001, 09/854,097, filed May 11, 2001, Serial No. 09/794,782, filed February 27, 2001, Serial No. 09/768,753, filed January 23, 2001, Serial No. 09/684,629, and filed October 6, 2000, Serial No. 09/597,812, filed June 19, 2000. This invention relates to gas discharge lasers and in particular to high repetition rate gas discharge lasers.

BACKGROUND OF THE INVENTION

Electric Discharge Gas Lasers

Electric discharge gas lasers are well known and have been available since soon after lasers were invented in the 1960s. A high voltage discharge between two electrodes excites a gaseous gain medium. A resonance cavity containing the gain medium permits stimulated amplification of light which is then extracted from the cavity in the form of a laser beam. Many of these electric discharge gas lasers are operated in a pulse mode.

Excimer Lasers

Excimer lasers are a particular type of electric gas discharge laser and have been known as such since the mid 1970s. A description of an excimer laser, useful for integrated circuit lithography, is described in U.S. Patent No. 5,023,884 issued June 11, 1991 entitled "Compact Excimer Laser." This patent has been assigned to Applicants' employer, and the patent is hereby incorporated herein by reference. The excimer laser described in Patent '884 is a high repetition rate pulse laser. In FIGS. 1 and 2, the principal elements of the laser 10 are shown. (FIG. 1 corresponds to FIG. 1 and FIG. 2 corresponds to FIG. 7 in Patent '884.) The discharges 22 are between two long (about 23 inches) electrodes 18 and 20 spaced apart by about 5/8 inch. Repetition rates of prior art lasers, like the one described, are typically within the range of about 100 to 2000 pulses per second. These high repetition rate lasers are usually provided with a gas circulation system. In the above referred to laser, this is done with a long squirrel-cage type fan 46, having about 23 blades 48. The fan blade structure is slightly longer than the electrodes 18 and 20 and provides sufficient circulation so that at pulse operating rates, the discharge disturbed gas between

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the electrodes is cleared between pulses. The shaft 130 of fan 46 is supported by two ball bearings 132 as shown in FIG. 2A which is FIG. 9 of Patent '884. The gas used in the laser contains fluorine which is extremely reactive. The fan rotor driving fan shaft 130 is sealed, within the same environmental system provided by housing structure members 12 and 14, by sealing member 136 as explained at column 9, line 45 of Patent '884, and the motor stator 140 is outside sealing member 136 and thus protected from the corrosive action of the fluorine gas. However, bearing 132 is subjected to the corrosive action of the chamber gas as is the lubrication used in the bearing. Corrosion of the bearings and bearing lubrication can contaminate the gas.

Modular Design

These excimer lasers, when used for integrated circuit lithography, are typically operated on a fabrication line "around-the-clock"; therefore down time can be expensive. For this reason most of the components are organized into modules which can be replaced normally within a few minutes.

Line Narrowing

Excimer lasers used for lithography must have its output beam reduced in bandwidth to a fraction of a picometer. This "line-narrowing" is typically accomplished in a line narrowing module (called a "line narrowing package" or "LNP") which forms the back of the laser's resonant cavity. This LNP typically is comprised of delicate optical elements including prisms, a mirror and a grating. As repetition rates increase maintaining stable performance by the LNP becomes a serious challenge.

Pulse Power

Electric discharge gas lasers of the type described in U.S. Patent No. 5,023,884 utilize an electric pulse power system such as that described in FIG. 3 to produce the electrical discharges, between the two electrodes. In such prior art systems, a direct current power supply 22 charges a capacitor bank called "the charging capacitor" or "C_0" 42 to a predetermined and controlled voltage called the "charging voltage" for each pulse. The magnitude of this charging voltage may be in the range of about 500 to 1000 volts. After C_0 has been charged to the predetermined voltage, a solid state switch 46 is closed allowing the electrical energy stored on C_0 to ring very quickly through a series of magnetic compression circuits comprising capacitor banks 52, 62 and 82 and inductors 48,

54 and 64 and a voltage transformer 56 to produce high voltage electrical potential in the range of about 16,000 volts across the electrode which produces the discharge which lasts about 50 ns.

In prior art systems on the market the time between the closing of the solid state switch and the discharge is in the range of about 5 microseconds; however, the charging of C_0 accurately to the pre-selected voltage has in the past required about 400 microseconds which was quick enough for pulse repetition rates of less than about 2,000 Hz. The reader should understand that accurate charging of C_0 is very important since the control of the voltage level on C_0 is in these systems the only practical control the laser operator has on the discharge voltage which in turn is the primary determiner of laser pulse energy.

Heat Exchanger

Prior art excimer lasers used for integrated circuit lithography typically require a system for cooling the laser gas which is heated both by the electric discharges and by the energy input through circulating fan discussed above. This is typically done with a water cooled, finned heat exchanger shown at 58 in FIG. 1. A doubling or more of the repetition rate of a laser more than doubles the heat generated in the laser primarily because power required to circulate the laser gas increases as the cube of the required gas velocity.

Control of Beam Quality

When used as a light source for integrated circuit lithography, the laser beam parameters (i.e., pulse energy, wavelength and bandwidth) typically are controlled to within very tight specifications. This requires pulse-to-pulse feedback control of pulse energy and somewhat slower feedback control of wavelength of the line narrowed output beam. A doubling or more of the pulse rate requires these feedback control systems to perform much faster.

What is needed is a better laser design for a pulse gas discharge laser for operation at repetition rates in the range of about 4,000 pulses per second.

SUMMARY OF THE INVENTION

The present invention provides gas discharge laser systems capable of reliable long-term operation in a production line capacity at repetition rates in the range of 8,000 to 10,000 pulses power second or greater. Preferred embodiments are configured as KrF, ArF and F_2 lasers used for light sources for integrated circuit lithography. Improvements include a modified high voltage power supply capable for charging an initial capacitor of a magnetic compression pulse power system to precise target voltages 6,000 to 10,000 times per second and a feedback control for monitoring pulse energy and determining the target voltages on a pulse-by-pulse basis. Several techniques are disclosed for removing discharge created debris from the discharge region between the laser electrodes during the intervals between discharges. In one embodiment the width of the discharge region is reduced from about 3 mm to about 1 mm so that a gas circulation system designed for 4,000 Hz operation could be utilized for 10,000 Hz operation. In other embodiments the gas flow between the electrodes is increased sufficiently to permit 10,000 Hz operation with a discharge region width of 3 mm. To provide these substantial increased gas flow rates, Applicants have disclosed preferred embodiments that utilize tangential fans of the prior art but with improved and more powerful motors and novel bearing designs. New bearing designs include both ceramic bearings and magnetic bearings. In other embodiments, some or all of the gas circulation power is provided with a blower located outside the laser chamber. The outside blower can be located in the laser cabinet or in a separate location.

The present invention also provides improvements to permit removal of additional heat resulting from the increased discharge rate and also additional heat resulting from the increased fan power. Embodiments of the present invention are applied to single chamber gas discharge laser system and to two chamber laser systems such as MOPA laser systems.

In this specification Applicants first described a laser system specifically designed for 4,000 Hz operation and refer to minor improvements for permitting substantial increases in pulse repetition. Applicants then describe systems for substantially increasing heat removal from the laser system and major modifications for providing substantial increases in laser gas flow. Applicants describe in detail the pulse power system designed to provide precise electrical pulses at rates up to 10,000 Hz or greater, detailed description of wavemeter and control equipment for monitoring and controlling the spectral properties of the laser pulses

at these pulse repetition rates and detailed description of Applicants' very fast response line narrowing equipment. Applicants also describe preferred laser purge technique and equipment, application of the present invention to MOPA systems and other useful improvements for these high repetition rate systems, including a beam delivery system and a pulse multiplier unit.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1, 2 and 2A show features of a prior art laser system.

FIG. 3 is a circuit diagram of a prior art pulse power system.

FIG. 4A shows a cross-section view of a laser chamber.

FIG. 4B shows a front view of a laser system.

FIG. 4C shows a main insulator with space for a preionizer ground rod.

FIG. 4D shows a cross-section of an electrode configuration.

FIG. 5 shows an electrical circuit diagram of a preferred pulse power system.

FIGS. 6A and 6B show two preferred resonant power supplies.

FIGS. 7, 7A and 8 show techniques for cooling pulse power components.

FIGS. 9A and 9B show views of a saturable inductor.

FIG. 10 shows a pulse transformer.

FIG. 10A shows a pulse transformer core.

FIG. 11 shows a technique for cooling a first saturable inductor.

FIGS. 12, 12A and 12B show a technique for cooling a second saturable inductor.

FIGS. 13 and 13A show views of the discharge region in the chamber of a preferred embodiment.

FIG. 13A(1) and 13A(2) show minor modification of the 13A configuration.

FIG. 13A(3-8) show features of a current return structure.

FIG. 13B shows an electrode configuration.

FIG. 13C shows a technique for enhanced cooling of laser gas.

FIG. 13D, E and F show techniques for avoiding downstream arcing.

FIG. 14 shows the layout of a wavemeter.

FIG. 14A, 14B, 14C and 14D are charts and graphs explaining the calculation of wavelengths and bandwidths.

FIG. 14E is a drawing of a wavemeter with enhanced illumination features.

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FIG. 15 is a block diagram showing components used for wavelength and bandwidth calculation.

FIG. 16 is a block diagram showing features of the laser system used for controlling the wavelength and pulse energy of the laser beam.

FIGS. 16A, 16B1, 16B2 and 16F are drawings showing techniques for controlling the LNP tuning mirror.

FIG. 16C shows the effect of piezoelectric control of the tuning mirror.

FIGS. 16D and 16E are diagrams showing wavelength control algorithms.

FIGS. 17, 17A, 17B and 17C show techniques for purging a grating face.

FIG. 18 shows a two-motor blower control system.

FIG. 18A shows a blower blade structure.

FIG. 18B shows a bearing configuration.

FIGS. 19, and FIGS. 19A-G shows features of a preferred N_2 purge system.

FIGS. 20, 20A and 20B show features of a preferred shutter.

FIGS. 21 and 21A show features of preferred water cooled finned heat exchanges.

FIG. 22 show features of a purge technique for purging high UV flux regions of the output beam train.

FIG. 23 shows a feature of a MOPA system with pulse stretching and beam delivery.

FIGS. 24A, B and C describe pulse-stretching technique.

FIG. 25 and 26 show techniques with the laser gas blower outside the discharge chamber.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS
HIGH REPETITION RATE KrF – ArF LASER

Described below is a state-of-the-art KrF laser used for integrated circuit lithography. It is a krypton fluoride (KrF) excimer laser designed to produce 7.5 mJ narrow-band approximately 248 nanometers (for example, 248.250 nm, 248,250 pm) pulses at pulse rates of 4 KHz. Specifications for these lasers include a bandwidth specification range of less than 0.5 pm (FWHM bandwidth) and less than 1.4 pm (95% integral bandwidth). Specifications also call for 3 sigma wavelength stability of less than 0.05 pm and a 30-pulse dose stability of less than 0.5 mJ. FIG. 4B is a front view of this preferred embodiment with the doors removed and many of the laser components identified. The laser is a modular unit and designed so that complete modules can be replaced very

quickly and easily in order to keep laser down time to a minimum. Going clockwise around FIG. 4B the identified components are:

- status lamp 1K indicating the operational status of the laser,
- control module 2K which controls the functioning of the laser based on input control signals from a hand held terminal (not shown) or a master controller of a lithography machine,
- compression head module 3K which is part of the lasers pulse power system and provides the final stages of pulse compression of electrical pulses which charge a peaking capacitor bank located on top of the laser chamber,
- stabilization module 4K also called the wavemeter which monitors the laser pulses and provides feedback signals controlling wavelength and pulse energy,
- automatic shutter module 5K with power meter,
- MFT power supply 6K providing high voltage power to a metal fluoride trap (a filter) located on the laser chamber module,
- left side blower motor 7K,
- laser chamber module 8K,
- interface module 9K providing interface circuits to mate the laser controls with lithography machine controls,
- cooling supply module 10K,
- cooling water distribution module 11K,
- laser gas supply module 12K,
- ventilation assembly 13K for venting the laser cabinet gases to outside atmosphere including a smoke detector,
- right side blower motor 14K,
- line narrowing module 15K also called the line narrowing package or LNP,
- right side blower motor controller 16K,
- left side blower motor controller 17K,
- commutator module 18K which contains a Co changing capacitor bank and an electrical circuit for initiating electrical pulses and for providing early stage pulse compression and pulse voltage amplification,
- resonant charger module 19K for providing very fast resonant charging of the Co capacitor bank,

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- high voltage power supply module 20K for producing high voltage DC power from standard facility three phase AC power,
- AC/DC distribution module 21K
- helium purge module (not shown)
- wave stability module (not shown)

FIG. 4A is a cross section drawing of a laser chamber 10A of a first preferred embodiment of the present invention. The principal chamber components are housing structure members 12A and 14A, cathode 18A and anode 20A upstream preionizer tube 60, peaking capacitor bank 62 and electrostatic trap unit 64 (all of which are similar to the prior art corresponding components shown in FIG. 1). The chamber includes a new anode support flow shaping structure 48, a new upper flow shaping structure 50, gas turning vanes 52, a new 5 inch diameter tangential type fan blade structure 46A and four water cooled heat exchanger units 58A. FIG. 13 show a similar alternate chamber configuration with a new current return 548.

FIG. 16 is a block diagram showing features of the laser system which are important for controlling the wavelength and pulse energy of the output beam.

Important improvements over prior art gas discharge lasers include:

1)   Improved flow path for circulating chamber laser gas
2)   Water cooled pulse power system
3)   Ultra fast wavemeter with fast control algorithm
4)   New high duty cycle LNP with combination PZT and stepper motor driven tuning mirror
5)   Large tangential fan with dual water-cooled brushless DC drive blower motors with special controllers
6)   Ultra pure nitrogen purge system for optics protection
7)   Sealed shutter with power meter
8)   Improved heat exchanger arrangement
9)   Beam seal system
10) Helium purge for LNP
11) Current return with ribs parallel to gas flow

12) Inductance plate for chamber impedance optimization

13) Electrode optimization for performance life.

Narrow Discharge Width

A preferred embodiment of the present invention designed to operate at pulse repetition rates of 4,000-10,000 KHz using a laser system designed for 4,000 Hz operation. In this embodiment the discharge region has been narrowed to about 1 to 1 ½ mm from earlier designs with a discharge region of about 3½ mm. (Preferred electrode designs to provide for a narrow discharge width are described in the following section). This permits the cleaning of the discharge region between the electrodes 18A and 20A with gas speeds of about 67 m/s. At this gas speed the debris from the pulse preceding each pulse is 0.5 cm downstream of the discharge region at the time of the discharge. To achieve these speeds, a 5-inch diameter of tangential fan unit is used (the length of the blade structure is 26 inches) and the rotational speed has been increased to about 3500 rpm. To achieve this performance the embodiment utilizes two motors rated at about 2 kw each which together deliver up to about 4 kw of drive power to the fan blade structure. At a pulse rate of 8000 Hz, for example, the discharge will add about 24 kw of heat energy to the laser gas. To remove the heat produced by the discharge along with the heat added by the fan four separate water-cooled finned heat exchanger units 58A are provided. The motors and the heat exchangers are described in detail below.

Heat Exchanger Components

A cross sectional drawing of one of the heat exchangers is shown in FIG. 21. The middle section of the heat exchanger is cut out but both ends are shown. FIG. 21A shows an enlarged view of the end of the heat exchanger which accommodates thermal expansion and contraction.

The components of the heat exchanger includes a finned structure 302 which is machined from solid copper (CU 15000) and contains twelve fins 303 per inch. Water flow is through an axial passage having a bore diameter of 0.33 inch. A plastic turbulator 306 located in the axial passage prevents stratification of water in the passage and prevents the formation of a hot boundary layer on the inside surface of the passage. A flexible flange unit 304 is a welded unit comprised of inner flange 304A, bellows 304B and outer flange

304C. The heat exchanger unit includes three c-seals 308 to seal the water flowing in the heat exchanger from the laser gas. Bellows 304B permits expansion and contraction of the heat exchanger relative to the chamber. A double port nut 400 connects the heat exchanger passage to a standard 5/16 inch positional elbow pipe fitting which in turn is connected to a water source. O-ring 402 provides a seal between nut 400 and finned structure 302.

The Turbulator

In a preferred embodiment, the turbulator is comprised of four off-the-shelf, long in-line mixing elements which are typically used to mix epoxy components and are available from 3M Corporation (Static Mixer, Part No. 06-D1229-00). The in-line mixers are shown at 306 in FIG. 21 and 21A. The in-line mixers force the water to flow along a generally helical path which reverses its clockwise direction about every pitch distance (which is 0.3 inch). The turbulator substantially improves heat exchanger performance. Tests by Applicants have shown that the addition of the turbulator reduces the required water flow by a factor of roughly 5 to maintain comparable gas temperature conditions.

Better Cooling Water Flow Control

For preferred embodiments of the present invention Applicants have added an on-off solenoid water control valve to the chamber cooling water supply. In previous designs cooling water is controlled with a proportional valve which in controlled based on a fast-acting temperature sensing the laser gas temperature. These proportional valves generally function very well at flows within certain ranges such as between 50 and 100 percent of the operating range of the valve. In order to provide good control over the entire cooling water flow range a digital on-off flow control valve is added in series with the proportional valve. These digital valves can be programmed

To operate at specific cycles such as one-second cycles with the valve open for a desired fraction of the one-second cycle and closed for the remainder of the one-second cycle. For example, the valve might be programmed to be open for about 0.2 second and closed for about 0.8 second. These digital valves are available from suppliers such as Asco Pneumatic & Fluid Power with offices in Florham Park, New Jersey. In a preferred embodiment the cooling water flow is controlled by a computer processor. The processor is programmed

with an algorithm which utilizes pulse rate date from the laser controls to anticipate cooling requirements.

INCREASED HEAT REMOVAL
Dual Pass Heat Exchanger

Laser systems currently in production by Applicants' employer utilize four in individual water-cooled finned heat exchangers. As shown in FIG. 13 and described above. The heat exchangers are single pass heat exchangers each are machined from a single block of copper. In a preferred embodiment which provides substantial improvement in performance is shown at 58B in FIG. 13C. In this case dual flow is provided using two water flow passages. Preferably cold water is injected in one of the two passages from each side of the chamber. This not only greatly increases the heat removal capacity of the heat exchangers, it also produces a much reduced temperature gradient between the two sides of the chamber.

A variation of the above design would be to connect the two passages at one end to produce a U-tube type heat exchanger. The advantages and disadvantages of this variation compared to the above design will be understood by those skilled in the art.

Monolithic Heat Exchanger

Laser systems currently being built by Applicants employer utilize four fined water-cooled heat exchangers as shown in FIG. 13. To provide additional cooling, the entire volume of the bottom portion of the chamber not taken up by the fan and the anode support bar is machined into large fins each about 0.5 mm thick with the fins spaced on 2 mm centers along the approximately 70 cm long chamber. Preferably, about eight precision holes are drilled through the fins and cooling water tubes of the same material as the chamber bottom are thermal fit in the holes to provide cooling for the chamber. Water can be injected from both sides as discussed above, one half the flow going each direction.

INCREASED LASER GAS FLOW VELOCITY
Laser Gas Flow Path

In this preferred embodiment, gas flow into and out of the discharge region has been greatly improved over prior art laser chambers. Vane structure 66 is designed to normalize gas velocity in the region 68, just downstream of the fan blade structure at

about 20 m/s. In the FIG. 13 embodiment the chamber top is machined to provide a similar flow shaping surface. The velocity of the gas then speeds up in the discharge region to the design velocity of 67 m/s. At about 4 inches downstream of the center of the discharge region, the flow cross section increases at an angle of 20 degrees from about 5/8 inch to about 4 inches before the gas is turned by four turning vanes 52. This permits recovery of a large percentage of the pressure drop through the discharge region. Whalebone shaped current return 548 as shown in FIG. 13A(1) is laser machined from 0.015 inch thick nickel alloy (UNS N04400) and bent into the shape as shown in FIGS. 13A(3) through 13A(8) so that the 23 ribs present minimum resistance to gas flow. Each rib has a cross section of 0.015 inch x 0.090 inch with the long dimension in a direction parallel to the gas flow direction.

<p align="center">Integrated Main Insulator</p>

In order to improve the flow path in the discharge region preferred embodiments of the present invention utilize a main insulator with one or more preionizer integrated into it. This basically combines the preionizer tube shown at 60 in FIG. 4A and the earlier version main insulator 50 in FIG. 4A. A cross-section drawing of the main insulator of a preferred embodiment is shown in FIG. 4C. The main insulator is shown at 50A and a slot for a ground rod is shown at 60A. The position of the cathode is shown at 18A1. The insulator is comprised of high-density alumina which is available from suppliers such as LTD Ceramics with offices in Newark, California. This design provides a substantial reduction in gas flow resistance permitting a significant increase in flow velocity with the same blower power. FIG. 4D shows a cathode-anode configuration showing this improved flow path as compared to configuration shown in FIG. 4A and even FIG. 13A(1) and FIG. 13A(2).

<p align="center">Increased Gas Flow</p>

If the width of the discharge region is kept at about 3.5 mm increases in repetition rate to the range of 10,000 Hz requires substantial increases in laser gas flow as compared to current commercial gas discharge lasers operating at 4,000 Hz. Several techniques to increase the gas flow as necessary to remove discharge debris from the discharge region between pulses are described herein.

Downstream Arcing

In prior art excimer chambers for a given gas flow rate, pulse repetition rate is limited by downstream arcing. Downstream arcing occurs when the debris of the previous pulse is just barely out of the discharge region at the time of the voltage potential between the electrodes approaches the discharge voltage. Arcs extends from the cathode along a path defined by the trailing edge of the debris to the anode. Downstream arcing produces extremely laser pulses with low energy and extremely poor quality. Thus, downstream arcing must be avoided and it is the phenomenon which limits pulse rate.

Suction at Anode

One preferred technique which is especially directed to improving flow in the immediate region of the anode is shown in FIG. 13A(3) which is just like the design shown in FIG. 13A(2) except a suction is provided immediately downstream of anode 542. In this embodiment a slot passageway 544C is provided along the length of anode 542 between anode 542 and insulator spacer 544B and through anode support bar 546 to cylindrical plenum 547. Plenum 547 connects to a pipe 549 external to the chamber as shown in FIG. 13D.

Blower 550 shown in FIG. 13E pulls laser gas from plenum 547 and discharges it through water-cooled heat exchanger 551 into plenum 552 at a pressure of about 1 atmosphere above the chamber pressure. Plenum 552 is created by drilling a 2.5 cm diameter hole in the chamber wall parallel to the long direction of the electrodes. Eight injection nozzles 553 are provided so that high pressure gas from plenum 552 is injected into the gas flow stream downstream of fan 46A at velocities substantially greater than the general gas flow velocity at that location. Thus, this extra flow loop provides additional gas cooling. The primary advantage however is that the extra flow loop provides laminar flow and also clears the region immediately downstream of the anode of discharge debris and as a result permits a substantial increase in the downstream arc-free repetition rate for a given general gas flow rate. Suction could also be provided downstream of the cathode by creating a plenum near the cathode similar to plenum 552. The plenum could be created in a modified version of main insulator 50 or in a cavity created between the cathode 541 and the insulator. Blower 550 could provide suction for both plenums.

The design shown in FIGS. 13D and 13E substantially complicates the chamber design requiring an additional blower which preferably would need to have motor with a canned rotor like the motors driving fan 46A. A simpler approach providing suction at the anode is shown in FIG. 13F. This design has been tested by Applicants and it substantially improves gas flow in the region immediately downstream of the anode. There is however, slight decrease in the general gas flow because a portion of the fan suction 555 is dedicated to providing the suction through the anode support bar 547.

Preferred embodiments of the present invention provides a large tangential fan driven by dual motors for circulating the laser gas. Components are shown in FIG. 4A, FIG. 13, FIG. 18 and FIG. 18A provides a gas flow between the electrode of 67 m/sec which is enough to clear a space of about 17 mm in the discharge region between 4,000 Hz pulses. At 10,000 Hz the space cleared is about 6.7 mm. This is about twice the width of the typical 3 to 3.5 mm discharge region of KrF and ArF lasers currently being utilized for laser lithography.

A cross section blade structure of the fan is shown as 64A in FIG. 4A. A prospective view is shown in FIG. 18A. The blade structure has a 5 inch diameter and is machined out of a solid aluminum alloy 6061-T6 bar stock. The individual blade in each section is slightly offset from the adjacent section as shown in FIG. 18A to minimize blade caused pressure perturbation in the discharge region. Preferably the individual blades have leading edges tapering to a knife edge so as to reduce reflections of discharge acoustic waves off the front edge of the blades during operation.

This embodiment as shown in FIG. 18 utilizes two water-cooled 3 phase brushless DC motors each with a magnetic rotor contained within a metallic pressure cup which separates the stator portion of the motors from the laser gas environment as described in U.S. Patent No. 4,950,840. In this embodiment, the pressure cup is thin-walled nickel alloy 400, 0.016 inch thick which functions as the laser gas barrier. The two motors 530 and 532 drive the same shaft and are programmed to rotate in opposite directions. Both motors are sensorless motors (i.e., they operate without position sensors). Right motor controller 534 which controls right motor 530 functions as a master controller controlling slave motor controller 536 via analog and digital signals to institute start/stop, current

command, current feedback, etc. Communication with the laser controller 24A is via a RS-232 serial port into master controller 534.

Larger Motors

The tangential fans depicted in FIGS. 18, 18A, 18B are the basic fan technology shown in FIGS. 2 and 2A which was patented by Applicants employer in 1991 (see U.S. Patent No. 5,023,884). Other improvements available to increase the laser gas velocity in the discharge region are fans with larger more powerful motors of the type described in U.S. Patent Application Serial No. 09/747,316 which has been incorporated by reference herein. That motor is rated at 4.5 kw so that two of these motors would provide about 9 kw of drive power for the 5-inch fan as compared to the two 2 kw motors described above. These larger fans would increase the velocity of the gas in the discharge region to about 90 m/s.

Better Ceramic Bearings

Faster fan speeds put additional stress on bearings. Deep-groove silicon nitride ball bearings have been shown to perform very well and exhibit reasonable longevity while supporting blower fans in fluorine-containing excimer laser chambers. The construction of this bearing requires silicon nitride balls and raceways plus a snap-in cage, typically made of PTFE (trade name Teflon), that keeps the balls separated from each other during operation.

The failure mode of this bearing is cage wear. Therefore, any improvement that minimizes cage wear will result in a longer lasting bearing. One improvement can be realized by changing the material of the cage to another fluorine-compatible, flexible material that has better mechanical (including abrasion resistance) and thermal properties. In this manner, the geometry of the cage is preserved. One suitable material is PCTFE (trade name Kel-F, which softens at temperatures 35F higher than PTFE). Tests have shown substantial reduction in erosion of Kel-F when compared to Teflon.

Another logical choice for cage material would be silicon nitride since it performs very well as balls and raceways. This however requires a geometry change since silicon nitride is not flexible and will not snap-in as the PCTFE will. FIG. 18B shows how this can be accomplished by constructing a two-piece cage 540A and 540B and locking the two pieces

together with a pin 542. The pin can be made from a flexible material like PTFE or PCTFE. Ceramic balls are shown at 541. An alternate arrangement is to alternate the silicon ball bearings with smaller separation balls in a cageless raceway. The separation balls are also silicon nitride. They carry no load act as spacers and rotate in directions opposite the bearing balls.

Another potential bearing material is zirconia or stainless steel coating with a diamond like coating (DLC) as available from Mineature Precision Bearing, a division of Timkin with offices in Keen, New Hampshire. Both the races and the ball are coated with the DLC. The substrater could also be zirconia. Tests have shown that in an F_2 atmosphere the bearing exhibit very low friction; therefore, it may be feasible to operate with these bearings with no lubrication.

Magnetic Bearings

Magnetic bearings may be provided in preferred embodiment to avoid bearings being limiting the useful life of the chamber and/or to permit higher speed operation. Descriptions of magnetic bearing systems are described in U.S. Patent No. 6,104,735 incorporated by reference herein.

Injector Circulator

In another preferred embodiment the fan and the main heat exchanger devices are removed from the discharge chamber and gas circulation is provided by high-pressure injection of about 10% to 20% of the circulating gas flow. Such an arrangement is depicted in FIG. 25. FIG. 25 shows a cross-section of the discharge chamber which basically consist of two cylinders about 70 cm long. The outside cylinder 600 has a diameter of about 30 cm and the inside cylinder 602 has a diameter of about 20 cm. The electrodes are located as shown at 604 which have conventional spacing of about 1.7 cm and the lengths of about 50 cm. The inside cylinder 602 provides an exhaust plenum for about 10 50 20 percent of the gas flow through nozzle type slit 606. This 10 to 20 percent of the flow exits cylinder 602 at one or both ends to gas pump 608 where it is pumped through water-cooled heat exchangers 610 to inlet plenum 612 formed of a third cylinder also about 70 cm long and plate which is welded to outside cylinder 600. Gas enters one or both ends of the plenum 612 and is injected into the circulating gas flow path through a slit type injection nozzle 614. The gas

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pressure between the two cylinders is at an average pressure of about 3 atmospheres gas pump 608 preferably a centrifugal blower sized to create sufficient pressure differentials to assure adequate flow velocity between the electrodes to permit desired discharge repetition rates in the range of 6,000 Hz to 10,000 Hz or greater. Preferably all portions of the flow loop subject to the laser gas is comprised of fluorine compatible materials. In preferred embodiments the drive for blower 608 a brushless DC motor having a canned rotor similar to the motors 530 and 532 described above and shown in FIG. 18 for driving the tangential fans.

Once Through Laser Gas Flow

Another technique for providing higher flow velocities between the electrodes is to provide for once through laser gas flow. In these embodiments the blower is also separated from the laser chamber but all of the flow through the electrodes is directed out of the discharge chamber 620 to blower unit 622. Such a system is shown in FIG. 26. The heat exchanger could be a separate unit or it could be contained in either the discharge chamber or in the same containment as the blower unit as in other embodiments the motor drive for the blower preferably comprises a canned rotor as described above. The blower may also be a hydraulic turbine driven blower such as that described in U.S. Patent No. 5,471,965 (incorporated by reference herein). In this case a magnetic coupling can be used to isolate the turbine drive from the fluorine containing laser gas. This drive will require an electric high pressure hydraulic fluid pump. The blower unit and the heat exchanger may be contained in a laser enclosure along with the discharge chamber or they could be contained in a separate enclosure or even a separate room within a fabrication plant. For this embodiment appropriate ducting and/or vanes are provided to distribute laser gas flow approximately equally along the length of the approximately 20 mm X 50 cm space between the electrodes 541A and 541B. Blower 622 and heat exchanger as well as the above ducts and vanes are designed using well known techniques to provide gas flows up to about 90 to 100 m/second through the discharge region between electrodes 541A and 541B. All parts of the flow path also must be constructed using fluorine compatible materials. The drive for blower 622 may be an electric motor or it could be a hydraulic turbine such as the drive in U.S. Patent No. 5,471,965.

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PULSE POWER FOR 6,000 Hz TO 10,000 Hz

Need for Fast Response

Operation of laser systems in accordance with the present invention requires precisely controlled electrical potentials in the range of about 12,000 V to 30,000 V be applied between the electrodes at repetition rates in the range of 6,000 Hz to 10,000 Hz (i.e., at intervals as short as about 100 micro seconds). As indicated in the background section, in prior art pulse power systems a charging capacitor bank is charged to a precisely predetermined control voltage and the discharge is produced by closing a solid state switch which allows the energy stored on the charging capacitor to ring through a compression-amplification circuit to produce the desired potential across the electrodes. The time between the closing of the switch to the completion of the discharge is only a few microseconds, (i.e., about 5 microseconds) but the charging of C_0 in prior art systems required a time interval much longer than 100 microseconds. It is possible to reduce the charging time by using a larger power supply or several power supplies in parallel. For example, Applicants are able to operate at 10,000 Hz using multiple prior art power supplies arranged in parallel. Increasing the voltage on the power supplier also reduces the charging time.

In this preferred embodiment, as shown in FIG. 5 Applicants utilize the same basic design as in the prior art shown in FIG. 3 for the portion of the pulse power system downstream of the solid state switch, but Applicants utilize a radically different technique for charging C_0.

Resonant Charging

Applicants have utilized two types of resonant charging systems for very fast charging of C_0. These systems can be described by reference to FIG.S 6A and 6B.

First Resonant Charger

An electrical circuit showing this preferred resonant charges is shown in FIG 6A. In this case, a standard dc power supply 200 having a 400 or 460 VAC/90 amp input and an 1200 VDC amp output is used. The power supply is a dc power supply adjustable from approximately 600 volts to 1200 volts. The power supply is attached directly to C-1

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eliminating the need for voltage feedback to the supply. When the supply is enabled it turns on and regulates a constant voltage on the C-1 capacitor. The performance of the system is somewhat independent of the voltage regulation on C-1 therefore only the most basic control loop is necessary in the power supply. Secondly the supply will be adding energy into the system whenever the voltage on C-1 falls below the voltage setting. This allows the power supply the entire time between initiation of laser pulses, (and even during laser pulses), to replenish energy transferred from C-1 to C_0. This further reduces the power supply peak current requirements over the prior art pulse power systems. The combination of requiring a supply with the most basic control loop, and minimizing the peak current rating of the supply to the average power requirements of the system reduces the power supply cost an estimated 50%. Additionally this preferred design provides vendor flexibility since constant current, fixed output voltage power supplies are readily available from multiple sources. Such power supplies are available from suppliers such as Elgar, Universal Voltronics, Kaiser and EMI.

Control Board

This power supply continuously charges a $1033\mu F$ capacitor 202 to the voltage level commanded by the control board 204. The control board 204 also commands IGBT switch 206 closed and open to transfer energy from capacitor 202 to capacitor 42. Inductor 208 sets up the transfer time constant in conjunction with capacitor 202 and 42 and limits the peak charging current. The inductance of value of this inductor has been reduced (from 140 micro Henrys used on a 4,000 Hz system) to 48 micro Henrys to permit very fast charging (less than 100 µs) of the CO capacitor 42. Control board 204 receives a voltage feedback 212 that is proportional to the voltage on capacitor 42 and a current feedback 214 that is proportional to the current flowing through inductor 208. From these two feedback signals control board 204 can calculate in real time the final voltage on capacitor 42 should IGBT switch 206 open at that instant of time. Therefore with a command voltage 210 fed into control board 204 a precise calculation can be made of the stored energy within capacitor 42 and inductor 208 to compare to the required charge voltage commanded 210. From this calculation, the control board 204 will determine the exact time in the charge cycle to open IGBT switch 206.

System Accuracy

After IGBT switch 206 opens the energy stored in the magnetic field of inductor 208 will transfer to capacitor 42 through the free-wheeling diode path 215. The accuracy of the real time energy calculation will determine the amount of fluctuation dither that will exist on the final voltage on capacitor 42. Due to the extreme charge rate of this system, too much dither may exist to meet a desired systems regulation need of $\pm0.05\%$. If so, additional circuitry may be utilized, such as for example, a de-qing circuit or a bleed-down circuit as discussed below.

Second Resonant Charger

A second resonant charger system is shown in FIG. 6B. This circuit is similar to the one shown in FIG. 6A. The principal circuit elements are:

> I1 – A three-phase power supply 300 with a constant DC current output.
>
> C-1 – A source capacitor 302 that is an order of magnitude or more larger than the existing C0 capacitor 42.
>
> Q1, Q2, and Q3 – Switches to control current flow for charging and maintaining a regulated voltage on C_0.
>
> D1, D2, and D3 – Provides current single direction flow.
>
> R1, and R2 – Provides voltage feedback to the control circuitry.
>
> R3 – Allows for rapid discharge of the voltage on C_0 in the event of a small over charge.
>
> L1 – Resonant inductor between C-1 capacitor 302 and C_0 capacitor 4-2 to limit current flow and setup charge transfer timing.
>
> Control Board 304 – Commands Q1, Q2, and Q3 open and closed based upon circuit feedback parameters.

An example of operation is as follows:

The difference in the circuit of FIG. 6B from that of 6A is the addition of switch Q2 and diode D3, known as a De-Qing switch. This switch improves the regulation of the circuit by allowing the control unit to short out the inductor during the resonant charging process. This "de-qing" prevents additional energy stored in the current of the charging inductor, L1, from being transferred to capacitor C_o.

Prior to the need for a laser pulse the voltage on C-1 is charged to 600-800 volts and switches Q1-Q3 are open. Upon command from the laser, Q1 would close. At this time current would flow from C-1 to C_0 through the charge inductor L1. As described in the previous section, a calculator on the control board would evaluate the voltage on C_0 and the current flowing in L1 relative to a command voltage set point from the laser. Q1 will open when the voltage on C_0 plus the equivalent energy stored in inductor L1 equals the desired command voltage. The calculation is:

$$V_f = [V_{C0s}^2 + ((L_1 * I_{L1s}^2)/C_0)]^{0.5}$$

Where:

V_f = The voltage on C_0 after Q1 opens and the current in L1 goes to zero.

V_{C0s} = The voltage on C_0 when Q1 opens.

I_{L1s} = The current flowing through L_1 when Q1 opens.

After Q1 opens the energy stored in L1 starts transferring to C_0 through D2 until the voltage on C_0 approximately equals the command voltage. At this time Q2 closes and current stops flowing to C_0 and is directed through D3. In addition to the "de-qing" circuit, Q3 and R3 from a bleed-down circuit to allow additional fine regulation of the voltage on C_0.

Switch Q3 of bleed down circuit 216 will be commanded closed by the control board when current flowing through inductor L1 stops and the voltage on C0 will be bled down to the desired control voltage; then switch Q3 is opened. The time constant of capacitor C_0 and resistor R3 should be sufficiently fast to bleed down capacitor C_0 to the command voltage without being an appreciable amount of the total charge cycle.

As a result, the resonant charger can be configured with three levels of regulation control. Somewhat crude regulation is provided by the energy calculator and the opening of switch Q1 during the charging cycle. As the voltage on C_0 nears the target value, the de-qing switch is closed, stopping the resonant charging when the voltage on C_0 is at or slightly above the target value. In a preferred embodiment, the switch Q1 and the de-qing switch is used to provide regulation with accuracy better than +/- 0.1%. If additional regulation is

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required, the third control over the voltage regulation could be utilized. This is the bleed-down circuit of switch Q3 and R3 (shown at 216 in FIG. 6B) to discharge C_o down to the precise target value.

Improvements Downstream of C_0

As indicated above, preferred embodiments of the pulse power system of the present invention as shown in FIG. 5 utilizes the same basic design as was used in the prior art systems described in FIG. 3. However, some significant improvements in that basic design were required for the approximate factor of 6 increase in heat load resulting from the greatly increased repetition rate. These improvements are discussed below.

Detailed Commutator and Compression Head Description

The principal components of commutator 40 and compression head 60 are shown in FIG. 3 and are discussed in the Background section with regard to the operation of the system. In this section, we describe details of fabrication of the commutator and the compression head.

Solid State Switch

Solid state switch 46 is an P/N CM 800 HA-34H IGBT switch provided by Powerex, Inc. with offices in Youngwood, Pennsylvania. In a preferred embodiment, two such switches are used in parallel.

Inductors

Inductors 48, 54 and 64 are saturable inductors similar to those used in prior systems as described in U.S. Patents 5,448,580 and 5,315,611 which are incorporated herein by reference. FIG. 7 shows a preferred design of the L_o inductor 48. In this inductor four conductors from the two IGBT switches 46B pass through sixteen ferrite toroids 49 to form part 48A an 8 inch long hollow cylinder of very high permeability material with an ID of about 1 inch and an OD of about 1.5 inch. Each of the four conductors are then wrapped twice around an insulating doughnut shaped core to form part 48B. The four conductors then connect to a plate which is in turn connected to the high voltage side of the C_1 capacitor bank 52.

A preferred sketch of saturable inductor 54 is shown in FIG. 8. In this case, the inductor is a single turn geometry where the assembly top and bottom lids 541 and 542 and center mandrel 543, all at high voltage, form the single turn through Five inductor magnetic cores. The outer housing 545 is at ground potential. The five magnetic cores are formed by windings of 0.0005" thick high permeability tape comprised of 50-50% Ni-Fe alloy provided by Magnetics of Butler, Pennsylvania or National Arnold of Adelanto, California. Fins 546 on the inductor housing facilitate transfer of internally dissipated heat to forced air cooling. In addition, a ceramic disk (not shown) is mounted underneath the reactor bottom lid to help transfer heat from the center section of the assembly to the module chassis base plate. FIG. 8 also shows the high voltage connections to one of the capacitors of the C_1 capacitor bank 52 and to a high voltage lead on one of the induction units of the 1:25 step up pulse transformer 56. The housing 545 is connected to the ground lead of unit 56.

A top and section view of the saturable inductor 64 is shown respectively in FIGS. 9A and 9B. In the inductors of this embodiment, flux excluding metal pieces 301, 302, 303 and 304 are added as shown in FIG. 9B in order to reduce the leakage flux in the inductors. These flux excluding pieces substantially reduce the area which the magnetic flux can penetrate and therefore help to minimize the saturated inductance of the inductor. The current makes five loops through vertical conductor rods in the inductor assembly around magnetic core 307. The current enters at 305 travels down a large diameter conductor in the center labeled "1" and up six smaller conductors on the circumference also labeled "1" as shown in FIG. 9A. The current then flows down two conductors labeled 2 on the inside, then up the six conductors labeled 2 on the outside then down flux exclusion metal on the inside then up the six conductors labeled 3 on the outside, then down the two conductors labeled 3 on the inside, then up the six conductors labeled 4 on the outside, then down the conductor labeled 4 on the inside. The flux exclusion metal components are held at half the full pulsed voltage across the conductor allowing a reduction in the safe hold-off spacing between the flux exclusion metal parts and the metal rods of the other turns. The magnetic core 307 is made up of three coils 307A, B and C formed by windings of 0.0005" thick high permeability tape 80-20% Ni-Fe alloy provided by Magnetics, Inc. of Butler, Pennsylvania or National Arnold of Adelanto, California. The reader should note that nano-crystaline materials such as VITROPERM™ available from

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VACUUM SCHITELZE GmbH, Germany and FINEMET™ from Hitachi Mekels, Japan could be used for inductors 54 and 64.

In prior art pulse power systems, oil leakage from electrical components has been a potential problem. In this preferred embodiment, oil insulated components are limited to the saturable inductors. Furthermore, the saturable inductor 64 as shown in FIG. 9B is housed in a pot type oil containing housing in which all seal connections are located above the oil level to substantially eliminate the possibility of oil leakage. For example, the lowest seal in inductor 64 is located at 308 as shown in FIG. 9B. Since the normal oil level is below the top lip of the housing 306, it is almost impossible for oil to leak outside the assembly as long as the housing is maintained in an upright condition.

Capacitors

Capacitor banks 42, 52, 62 and 82 (i.e., C_o, C_1, C_{p-1} and C_p) as shown in FIG. 5 are all comprised of banks of off-the-shelf capacitors connected in parallel. Capacitors 42 and 52 are film type capacitors available from suppliers such as Vishay Roederstein with offices in Statesville, North Carolina or Wima of Germany. Applicants preferred method of connecting the capacitors and inductors is to solder them to positive and negative terminals on special printed circuit board having heavy nickel coated copper leads in a manner similar to that described in U.S. Patent No. 5,448,580. Capacitor bank 62 and 82 is composed of a parallel array of high voltage ceramic capacitors from vendors such as Murata or TDK, both of Japan. In a preferred embodiment for use on this KrF laser, capacitor bank 82 (i.e., C_p) is comprised of a bank of thirty three 0.3 nF capacitors for a capacitance of 9.9 nF; C_{p-1} is comprised of a bank of twenty four 0.40 nF capacitors for a total capacitance of 9.6 nF; C_1 is a 5.7 µF capacitor bank and C_o is a 5.3 µF capacitor bank.

Pulse Transformer

Pulse transformer 56 is also similar to the pulse transformer described in U.S. Patent Nos. 5,448,580 and 5,313,481; however, the pulse transformers of a preferred embodiment has only a single turn in the secondary winding and 24 induction units equivalent to 1/24 of a single primary turn for an equivalent step-up ratio of 1:24. A drawing of pulse transformer 56 is shown in FIG. 10. Each of the 24 induction units comprise an aluminum spool 56A having two flanges (each with a flat edge with threaded bolt holes) which are

bolted to positive and negative terminals on printed circuit board 56B as shown along the bottom edge of FIG. 10. (The negative terminals are the high voltage terminals of the twenty four primary windings.) Insulators 56C separates the positive terminal of each spool from the negative terminal of the adjacent spool. Between the flanges of the spool is a hollow aluminum cylinder 1 1/16 inches long with a 0.875 OD with a wall thickness of about 1/32 inch. The spool is wrapped with one inch wide, 0.7 mil thick Metglas™ 2605 S3A and a 0.1 mil thick mylar film until the OD of the insulated Metglas™ wrapping is 2.24 inches. A prospective view of a single wrapped spool forming one primary winding is shown in FIG. 10A.

The secondary of the transformer is a single ¼ inch OD stainless steel rod mounted within a tight fitting insulating tube of PTFE (Teflon®). The winding is in four sections as shown in FIG. 10. The low voltage end of stainless steel secondary as shown at 56D in FIG. 10 is tied to the primary HV lead on printed circuit board 56B at 56E, the high voltage terminal is shown at 56F. As a result, the transformer assumes an auto-transformer configuration and the step-up ratio becomes 1:25 instead of 1:24. Thus, an approximately - 1400 volt pulse between the + and - terminals of the induction units will produce an approximately -35,000 volt pulse at terminal 56F on the secondary side. This single turn secondary winding design provides very low leakage inductance permitting extremely fast output rise time.

Details of Laser Chamber Electrical Components

The Cp capacitor 82 is comprised of a bank of thirty-three 0.3 nf capacitors mounted on top of the chamber pressure vessel. The electrodes are about 28 inches long which are separated by about 0.5 to 1.0 inch. The preferred gap separation is 16.5 mm for KrF. (The preferred separation for ArF is 13.5 mm.) Preferred electrodes are described below. In this embodiment, the top electrode is referred to as the cathode and the bottom electrode is connected to ground as indicated in FIG. 5 and is referred to as the anode. The inductance labeled Lp in FIG. 5 is referred to by Applicants as the "head inductance". This inductance represents the inductance of the circuit formed by the connection between Cp and the cathode 84, the discharge region and the connection between the anode and Cp which is comprised of anode and a current return structure such as the one shown at 548 in FIG. 13A (1).

Water Cooling of Components

To accommodate greater heat loads water cooling is provided which is better able to support operation at this higher average power mode in addition to the normal forced air cooling provided by cooling fans inside the laser cabinet.

One disadvantage of water cooling has traditionally been the possibility of leaks near the electrical components or high voltage wiring. This specific embodiment substantially avoids that potential issue by utilizing single solid sections of cooling tubing that is routed within a module to cool those components that normally dissipate the majority of the heat deposited in the module. Since no joints or connections exist inside the module enclosure and the cooling tubing is a continuous piece of solid metal (e.g. copper, stainless steel, etc.), the chances of a leak occurring within the module are greatly diminished. Module connections to the cooling water are therefore made outside the assembly sheet metal enclosure where the cooling tubing mates with a quick-disconnect type connector.

Detailed Commutator Description

In the case of the commutator module 18K as shown in FIG. 4B a water cooled saturable inductor 54A is provided as shown in FIG. 11 which is similar to the inductor 54 shown in FIG. 8 except the fins of 54 are replaced with a water cooled jacket 54A1 as shown in FIG. 11. The cooling line 54A2 is routed within the module to wrap around jacket 54A1 and through an aluminum base plate (as described below) where the IGBT switches and Series diodes are mounted. These three components make up the majority of the power dissipation within the module. Other items that also dissipate heat (snubber diodes and resistors, capacitors, etc.) are cooled by forced air provided by the two fans in the rear of the module.

Since the jacket 54A1 is held at ground potential, there are no voltage isolation issues in directly attaching the cooling tubing to the reactor housing. This is done by press-fitting the tubing into a dovetail groove cut in the outside of the housing as shown at 54A3 and using a thermally conductive compound to aid in making good thermal contact between the cooling tubing and the housing.

Cooling High Voltage Components

Although the IGBT switches "float" at high voltage, they are mounted on an aluminum base electrically isolated from the switches by a 1/16 inch thick alumina plate. The aluminum base plate which functions as a heat sink and operates at ground potential and is much easier to cool since high voltage isolation is not required in the cooling circuit. A drawing of a water cooled aluminum base plate is shown in FIG. 7A. In this case, the cooling tubing is pressed into a groove in an aluminum base on which the IGBT's are mounted. As with the inductor 54a, thermally conductive compound is used to improve the overall joint between the tubing and the base plate.

The series diodes also "float" at high potential during normal operation. In this case, the diode housing typically used in the design provides no high voltage isolation. To provide this necessary insulation, the diode "hockey puck" package is clamped within a heat sink assembly which is then mounted on top of a ceramic base that is then mounted on top of the water-cooled aluminum base plate. The ceramic base is just thick enough to provide the necessary electrical isolation but not too thick to incur more than necessary thermal impedance. For this specific design, the ceramic is 1/16" thick alumina although other more exotic materials, such as beryllia, could also be used to further reduce the thermal impedance between the diode junction and the cooling water.

A second embodiment of a water cooled commutator utilizes as single cold plate assembly which is attached to the chassis base plate for the IGBT's and the diodes. The cold plate may be fabricated by brazing single piece nickel tubing to two aluminum "top" and "bottom" plates. As described above, the IGBT's and diodes are designed to transfer their heat into the cold plate by use of the previously mentioned ceramic disks underneath the assembly. In a preferred embodiment of this invention, the cold plate cooling method is also used to cool the IGBT and the diodes in the resonant charger. Thermally conductive rods or a heat pipe can also be used to transfer heat from the outside housing to the chassis plate.

Detailed Compression Head Description

The water-cooled compression head (see FIG. 5 for the components of the compression head) is similar in the electrical design to a prior art air-cooled version (the same type

ceramic capacitors are used and similar material is used in the design saturable inductor 64). The primary differences in this case are that the module must run at higher rep-rates and therefore, higher average power. In the case of the compression head module, the majority of the heat is dissipated within the modified saturable inductor 64A. Cooling the subassembly is not a simple matter since the entire housing operates with short pulses of very high voltages. The solution to this issue as shown in FIGS. 12, 12A and 12B is to inductively isolate the housing from ground potential. This inductance is provided by wrapping the cooling tubing around two cylindrical forms that contain a ferrite magnetic core. Both the input and output cooling lines are coiled around cylindrical portions of a ferrite core formed of the two cylindrical portions and the two ferrite blocks as shown in FIGS. 12, 12A and 12B.

The ferrite pieces are made from CN-20 material manufactured by Ceramic Magnetics, Inc. of Fairfield, New Jersey. A single piece of copper tubing (0.187" diameter) is press fit and wound onto one winding form, around the housing 64A1 of inductor 64A and around the second winding form. Sufficient length is left at the ends to extend through fittings in the compression head sheet metal cover such that no cooling tubing joints exist within the chassis.

The inductor 64A comprises a dovetail groove as shown at 64A2 similar to that used in the water-cooled commutator first stage reactor housing. This housing is much the same as previous air-cooled versions with the exception of the dovetail groove. The copper cooling-water tubing is press fit into this groove in order to make a good thermal connection between the housing and the cooling-water tubing. Thermally conductive compound is also added to minimize the thermal impedance.

The electrical design of inductor 64A is changed slightly from that of 64 shown in FIGS 9A and 9B. Inductor 64A provides only two loops (instead of five loops) around magnetic core 64A3 which is comprised of four coils of tape (instead of three).

As a result of this water-cooled tubing conductive path from the output potential to ground, the bias current circuit is now slightly different as shown in FIG. 5. As before, bias current is supplied by a dc-dc converter in the commutator through a cable into the

compression head. The current passes through the "positive" bias inductor L_{B2} and is connected to the Cp-1 voltage node. The current then splits with a portion returning to the commutator through the HV cable (passing through the transformer secondary to ground and back to the dc-dc converter). The other portion passes through the compression head reactor Lp-1 (to bias the magnetic switch) and then through the cooling-water tubing "negative" bias inductor L_{B3} and back to ground and the dc-dc converter. By balancing the resistance in each leg, the designer is able to ensure that sufficient bias current is available for both the compression head reactor and the commutator transformer.

The "positive" bias inductor L_{B2} is made very similarly to the "negative" bias inductor L_{B3}. In this case, the same ferrite bars and blocks are used as a magnetic core. However, two 0.125" thick plastic spacers are used to create an air gap in the magnetic circuit so that the cores do not saturate with the dc current. Instead of winding the inductor with cooling-water tubing, 18 AWG teflon wire is wound around the forms.

Quick Connections

In this preferred embodiment, three of the pulse power electrical modules utilize blind mate electrical connections so that all electrical connections to the portions of the laser system are made merely by sliding the module into its place in the laser cabinet. These are the AC distribution module, the power supply module and the resonant charger module. In each case a male or female plug on the module mates with the opposite sex plug mounted at the back of the cabinet. In each case two approximately 3-inch end tapered pins on the module guide the module into its precise position so that the electrical plugs properly mate. The blind mate connectors such as AMP Model No. 194242-1 are commercially available from AMP, Inc. with offices in Harrisburg, Pennsylvania. In this embodiment connectors are for 460 volt AC, 400 volt AC, 1200 volt DC (power supply out and resonant charger in) and several signal voltages. These blind mate connections permit these modules to be removed for servicing and replacing in a few seconds or minutes. In this embodiment blind mate connections are not used for the commutator module since the output voltage of the module is in the range of 20,000 to 30,000 volts. Instead, a typical high voltage connector is used.

Feeds to Cathode
(Technique For Increasing Inductance)

As indicated in FIG. 5 and explained above, the peaking capacitor bank, C_p, 82 consists of a bank of 33 0.3 nF capacitors. These are connected on the bottom of the capacitors to ground (i.e., the chamber head) and at the top to a metal plate called the corona shield. The corona shield is in turn connected to the cathode with 15 metal rods which are called down-comers which pass through a single piece main insulator and are screwed into the top of cathode 541 as shown in FIG. 13A. The single piece insulator is as described in U.S. Patent No. 6,208,674 incorporated herein by reference. In some cases increased inductance in the high voltage portion of the pulse power circuit is desirable. Such an increase can result in an increase in the laser pulse duration. Applicants have determined that a preferred method of producing this increased inductance is to provide short (for example, about 1 ¼ inch) standoff rods connecting each of the capacitors in the C_p capacitor bank and the down-comer rods to the corona plate. This increases the length of the electrical path between C_p and the cathode substantially increasing the inductance in this part of the circuit. The amount of increase in inductance can be tailored by choice of length of the stand-off rods. Another technique for increasing the inductance is to eliminate some of the current return ribs in the current return structure shown in FIG. 13A(3) and/or some of the 15 downcomers connecting the corona shield to the cathode. Eliminating some of the downcomers at each end of the cathode has another advantage of about 3.5mm.

Discharge Components

FIGS. 13 and 13A(1) show details of an improved discharge configuration utilized in preferred embodiments of the present invention. This configuration includes an electrode configuration that Applicants call a blade-dielectric electrode. In this design, the anode 540 comprises a blunt blade shaped electrode 542 with dielectric spacers 544 mounted on both sides of the anode as shown to improve the gas flow in the discharge region. The spacers are attached to anode support bar 546 with screws at each end of the spacers beyond the discharge region. The screws allow for thermal expansion slippage between the spacers and the bar. The anode is 26.4 inches long and 0.439 inches high. It is 0.284 inches wide at the bottom. The width at the top is chosen to approximately determine the desired discharge width. For the 10,000Hz embodiment the width is about

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1.0 to 1.5 mm. It is attached to flow shaping anode support bar 546 with screws through sockets that allow differential thermal expansion of the electrode from its center position. The anode is comprised of a copper based alloy preferably C36000, C95400, or C19400. Cathode 541 has a cross section shape as shown in FIG. 13A. A preferred cathode material is C36000. Additional details of this blade dielectric configuration are provided in U.S. Patent Application Serial No. 09/768,753 incorporated herein by reference. The current return 548 in this configuration is comprised of a whale bone shaped part with 27 ribs equally spaced along the length of electrode 542, the cross section of which is shown in FIG. 13A (1). As described above, the current return is fabricated from sheet metal and the whale-bone ribs (each having cross-section dimensions of about 0.15 inch x 0.09 inch) are twisted so that the long dimension of each rib is in the direction of current flow.

An alternative dielectric spacer design for the anode is shown in FIG. 13A2 to improve flow even more. In this case the spacers mate more perfectly with the flow shaping anode support bar to provide a better gas flow path. Applicants call this their "fast back" blade dielectric anode design.

<div align="center">Insulator Covered Electrodes</div>

A preferred electrode configuration is shown in FIGS. 13B. In this case both the cathode 541C and anode 542C are comprised of brass. A portion or all of the surfaces of the electrodes are covered with an alumina layer 600 and 602 to a thickness of about 125 microns. Preferably, the alumina is applied to the surface with a plasma spray technique. A very large number of holes 604 and 606 are then drilled through the alumina to the brass substrate as shown in FIG. 13B at 604 and 606. The holes preferably are between 50 micron to 200 microns in diameter on both the cathode and the anode. A preferred dimension is about 100 microns. The holes may be drilled with an excimer laser. Applicants recommend a hole density of about 10 holes per mm^2 for an exposed area of about 5-10%. This electrode design is expected to provide extremely long-life electrodes. It also permits precise control over the width of the discharge. Erosion rates are reduced by orders of magnitude since the discharge surfaces are to a great extent protected from fluorine attack by the alumina cover. Cathode erosion due to sputtering is also substantially reduced since the cathode configuration provides hollow cathode effects in

which spattered metal ions recombine with the brass substrate inside the holes instead of forming metal fluorides.

ULTRA FAST WAVEMETER WITH FAST CONTROL ALGORITHM
Controlling Pulse Energy, Wavelength and Bandwidth

Prior art excimer lasers used for integrated circuit lithography are subject to tight specifications on laser beam parameters. This has typically required the measurement of pulse energy, bandwidth and center wavelength for every pulse and feedback control of pulse energy and bandwidth. In prior art devices the feedback control of pulse energy has been on a pulse-to-pulse basis, i.e., the pulse energy of each pulse is measured quickly enough so that the resulting data can be used in the control algorithm to control the energy of the immediately following pulse. For a 1,000 Hz system this means the measurement and the control for the next pulse must take less than 1/1000 second. For a 4000 Hz system speeds need to be four times as fast as the 1000 Hz system and for 10,0000 Hz, speeds need to be 10 times as fast. A technique for controlling center wavelength and measuring wavelength and bandwidth is described in U.S. Patent No. 5,025,455 System, and Method of Regulating the Wavelength of a Light Beam and in U.S. Patent No. 5,978,394, Wavelength and System for an Excimer Laser. These patents are incorporated herein by reference.

Wavelength and bandwidths have been measured on a pulse to pulse basis for every pulse, but typically the feedback control of wavelength has taken about 7 milli-seconds because prior art techniques for controlling center wavelength have taken several milli-seconds. Faster control is needed.

Preferred Embodiment for Fast Measurement and Control of Beam Parameters
A preferred embodiment of the present invention is an excimer laser system capable of operation in the range of 4,000 Hz to 10,000 Hz with very fast measurement of laser beam parameters and very fast control of pulse energy and center wavelength. The beam parameter measurement and control for this laser is described below.

The wavemeter used in the present embodiment is similar to the one described in U.S. Patent No. 5,978,394 and some of the description below is extracted from that patent.

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Measuring Beam Parameters

FIG. 14 shows the layouts of a preferred wavemeter unit 120, an absolute wavelength reference calibration unit 190, and a wavemeter processor 197.

The optical equipment in these units measure pulse energy, wavelength and bandwidth. These measurements are used with feedback circuits to maintain pulse energy and wavelength within desired limits. The equipment calibrates itself by reference to an atomic reference source on the command from the laser system control processor.

As shown in FIG. 14, the laser output beam intersects partially reflecting mirror 170, which passes about 95.5% of the beam energy as output beam 33 and reflects about 4.5% for pulse energy, wavelength and bandwidth measurement.

Pulse Energy

About 4% of the reflected beam is reflected by mirror 171 to energy detector 172 which comprises a very fast photo diode 69 which is able to measure the energy of individual pulses occurring at the rate of 4,000 to 1000 pulses per second. A typical pulse energy is about 7.5 mJ, and the output of detector 69 is fed to a computer controller which uses a special algorithm to adjust the laser charging voltage to precisely control the pulse energy of future pulses based on stored pulse energy data in order to limit the variation of the energy of individual pulses and the integrated energy of bursts of pulses.

Linear Photo Diode Array

The photo sensitive surface of linear photo diode array 180 is depicted in detail in FIG. 14A. The array is an integrated circuit chip comprising 1024 separate photo diode integrated circuits and an associated sample and hold readout circuit. The photo diodes are on a 25 micrometer pitch for a total length of 25.6 mm (about one inch). Each photo diode is 500 micrometer long.

Photo diode arrays such as this are available from several sources. A preferred supplier is Hamamatsu. In our preferred embodiment, we use a Model S3903-1024Q which can be read at the rate of up to 4×10^6 pixels/sec on a FIFO basis in which complete 1024 pixel

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scans can be read at rates of 4,000 Hz or greater. The PDA is designed for 2×10^6 pixel/sec operation but Applicants have found that it can be over-clocked to run much faster, i.e., up to 4×10^6 pixel/sec. For pulse rates greater than 4,000 Hz, Applicants can use the same PDA but only a fraction (such as 60%) of the pixels are normally read on each scan.

Faster Linear Arrays

For 10,000 Hz operation with pulse-to-pulse data analysis, are available for wavelength and bandwidth calculation. At 5×10^6 pixels per second about one-half of the pixels on the 1024 pixel array could be read for each pulse of all of the time between pulses were used for reading data. One solution would be to monitor wavelength and bandwidth on less than every pulse, such as every fourth pulse or every second pulse. Another solution is to program the wavemeter controls so that only selected pixels are read based on use of a predictive algorithm which projects the location of the fringe data on the array using historical data. A more desirable solution is to find a faster array. Applicants have determined that back-illuminated CCD array can be utilized to provide response time of about 10 to 15×10^6 pixels per second. A preferred array is Model SXXX1002 available from Hamamatsu with offices in Tokyo, Japan.

Another technique for speeding up the wavelength analysis is to utilize a digital signal processor located at the wavemeter to perform wavelength calculation as described below.

Coarse Wavelength Measurement

About 4% of the beam which passes through mirror 171 is reflected by mirror 173 through slit 177 to mirror 174, to mirror 175, back to mirror 174 and onto echelle grating 176. The beam is collimated by lens 178 having a focal length of 458.4 mm. Light reflected from grating 176 passes back through lens 178, is reflected again from mirrors 174, 175 and 174 again, and then is reflected from mirror 179 and focused onto the left side of 1024-pixel linear photo diode array 180 in the region of pixel 600 to pixel 950 as shown in the upper part of FIG. 14B (Pixels 0-599 are reserved for fine wavelength measurement and bandwidth.) The spatial position of the beam on the photo diode array is a coarse measure of the relative nominal wavelength of the output beam. For example, as shown in

FIG. 14B, light in the wavelength range of about 193.350 pm would be focused on pixel 750 and its neighbors.

Calculation of Coarse Wavelength

The coarse wavelength optics in wavemeter module 120 produces a rectangular image of about 0.25 mm x 3 mm on the left side of photo diode array 180. The ten or eleven illuminated photo diodes will generate signals in proportion to the intensity of the illumination received (as indicated in FIG. 14C) and the signals are read and digitized by a processor in wavemeter controller 197. Using this information and an interpolation algorithm controller 197 calculates the center position of the image.

This position (measured in pixels) is converted into a coarse wavelength value using two calibration coefficients and assuming a linear relationship between position and wavelength. These calibration coefficients are determined by reference to an atomic wavelength reference source as described below. For example, the relationship between image position and wavelength might be the following algorithm:

$$\lambda = (2.3 \text{ pm / pixel}) \, P + 191{,}625 \text{ pm}$$

where P = coarse image central positions.

Alternatively, additional precision could be added if desired by adding a second order term such as "$+(\ )\,P^2$.

Fine Wavelength Measurement

About 95% of the beam which passes through mirror 173 as shown in FIG. 14 is reflected off mirror 182 through lens 183 onto a diffuser (preferably a diffraction diffuser as explained in a following section entitled "Improved Etalon") at the input to etalon assembly 184. The beam exiting etalon 184 is focused by a 458.4 mm focal length lens in the etalon assembly and produces interference fringes on the middle and right side of linear photo diode array 180 after being reflected off two mirrors as shown in FIG. 14.

The spectrometer must measure wavelength and bandwidth substantially in real time. Because the laser repetition rate may be 4,000 Hz to 6,000 Hz, it is necessary to use

algorithms which are accurate but not computationally intensive in order to achieve the desired performance with economical and compact processing electronics. Calculation algorithm therefore preferably should use integer as opposed to floating point math, and mathematical operations should preferably be computation efficient (no use of square root, sine, log, etc.).

The specific details of a preferred algorithm used in this preferred embodiment will now be described. FIG. 14D is a curve with 5 peaks as shown which represents a typical etalon fringe signal as measured by linear photo diode array 180. The central peak is drawn lower in height than the others. As different wavelengths of light enter the etalon, the central peak will rise and fall, sometimes going to zero. This aspect renders the central peak unsuitable for the wavelength measurements. The other peaks will move toward or away from the central peak in response to changes in wavelength, so the position of these peaks can be used to determine the wavelength, while their width measures the bandwidth of the laser. Two regions, each labeled data window, are shown in FIG. 14D. The data windows are located so that the fringe nearest the central peak is normally used for the analysis. However, when the wavelength changes to move the fringe too close to the central peak (which will cause distortion and resulting errors), the first peak is outside the window, but the second closest peak will be inside the window, and the software causes the processor in control module 197 to use the second peak. Conversely, when the wavelength shifts to move the current peak outside the data window away from the central peak the software will jump to an inner fringe within the data window. The data windows are also depicted on FIG. 14B.

Fast Computation of Spectral Values

For very fast computation of bandwidth for each pulse at repetition rates up to the range of 4,000 Hz to 10,000 Hz a preferred embodiment uses the hardware identified in FIG. 15. The hardware includes a microprocessor 400, Model MPC 823 supplied by Motorola with offices in Phoenix, Arizona; a programmable logic device 402, Model EP 6016QC240 supplied by Altera with offices in San Jose, California; an executive and data memory bank 404; a special very fast RAM 406 for temporary storage of photodiode array data in table form; a third 4X1024 pixel RAM memory bank 408 operating as a memory buffer; and an analog to digital converter 410.

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As explained in U.S. Patent Nos. 5,025,446 and U.S. Patent No. 5,978,394, prior art devices were required to analyze a large mass of PDA data pixel intensity data representing interference fringes produced by etalon 184 an photodiode array 180 in order to determine center line wavelength and bandwidth. This was a relatively time consuming process even with a computer processor because about 400 pixel intensity values had to be analyzed to look for and describe the etalon fringes for each calculation of wavelength and bandwidth. A preferred embodiment of the present invention greatly speeds up this process by providing a processor for finding the important fringes which operates in parallel with the processor calculating the wavelength information.

The basic technique is to use programmable logic device 402 to continuously produce a fringe data table from the PDA pixel data as the pixel data are produced. Logic device 402 also identifies which of the sets of fringe data represent fringe data of interest. Then when a calculation of center wavelength and bandwidth are needed, microprocessor merely picks up the data from the identified pixels of interest and calculates the needed values of center wavelength and bandwidth. This process reduces the calculation time for microprocessor by about a factor of about 10.

Specific steps in the process of calculating center wavelength and bandwidth are as follows:

1)   With PDA 180 clocked to operate at 2.5 MHz, PDA 180 is directed by processor 400 to collect data at a from pixels 1 to 600 at a scan rate of 4,000 Hz and to read pixels 1 to 1028 at a rate of 100 Hz.

2)   The analog pixel intensity data produced by PDA 180 is converted from analog intensity values into digital 8 bit values (0 to 255) by analog to digital converter 410 and the digital data are stored temporarily in RAM buffer 408 as 8 bit values representing intensity at each pixel of photodiode array 180.

3)   Programmable logic device 402 analyzes the data passing out of RAM buffer 408 continuously on an almost real time basis looking for fringes, stores all the data in RAM memory 406, identifies all fringes for each pulse, produces a table of fringes for each pulse and stores the tables in RAM 406, and identifies for further analysis

one best set of two fringes for each pulse. The technique used by logic device 402
is as follows:

A)   PLD 402 analyzes each pixel value coming through buffer 408 to
        determine if it exceeds an intensity threshold while keeping track of
        the minimum pixel intensity value. If the threshold is exceeded this
        is an indication that a fringe peak is coming. The PLD identifies
        the first pixel above threshold as the "rising edge" pixel number and
        saves the minimum pixel value of the pixels preceding the "rising
        edge" pixel. The intensity value of this pixel is identified as the
        "minimum" of the fringe.

B)   PLD 402 then monitors subsequent pixel intensity values to search
        for the peak of the fringe. It does this by keeping track of the
        highest intensity value until the intensity drops below the threshold
        intensity.

C)   When a pixel having a value below threshold is found, the PLD
        identifies it as the falling edge pixel number and saves the
        maximum value. The PLD then calculates the "width" of the fringe
        by subtracting the rising edge pixel number from the falling edge
        pixel number.

D)   The four values of rising edge pixel number, maximum fringe
        intensity, minimum fringe intensity and width of the fringe are
        stored in the circular table of fringes section of RAM memory bank
        406. Data representing up to 15 fringes can be stored for each pulse
        although most pulses only produce 2 to 5 fringes in the two
        windows.

E)   PLD 402 also is programmed to identify with respect to each pulse
        the "best" two fringes for each pulse. It does this by identifying the
        last fringe completely within the 0 to 199 window and the first
        fringe completely within the 400 to 599 window.

The total time required after a pulse for (1) the collection of the pixel data, and (2) the
formation of the circular table of fringes for the pulse is less than 200 micro seconds. The

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principal time saving advantages of this technique is that the search for fringes is occurring as the fringe data is being read out, digitized and stored. Once the two best fringes are identified for a particular pulse, microprocessor 400 secures the raw pixel data in the region of the two fringes from RAM memory bank 406 and calculates from that data the bandwidth and center wavelength. To shorten the calculation time further, microprocessor 400 could be replaced with a fast digital signal processor (called a DSP) of a type made by Motorola and Texas Instruments (such s Motorola chip DPS56303). The DSP could be located at the wavemeter so that the only data transmitted from the wavemeter to the laser main controls are final values need for beam control. This permits a reduction in the calculation time to substantially less than 100 microseconds. The calculation is as follows:

Typical shape of the etalon fringes are shown in FIG. 14D. Based on the prior work of PLD 402 the fringe having a maximum at about pixel 180 and the fringe having a maximum at about pixel 450 will be identified to microprocessor 400. The pixel data surrounding these two maxima are analyzed by microprocessor 400 to define the shape and location of the fringe. This is done as follows:

A)   A half maximum value is determined by subtracting the fringe minimum from the fringe maximum dividing the difference by 2 and adding the result to the fringe minimum. For each rising edge and each falling edge of the two fringes the two pixels having values of closest above and closest below the half maximum value. Microprocessor then extrapolates between the two pixel values in each case to define the end points of D1 and D2 as shown in FIG. 18B with a precision of 1/32 pixel. From these values the inner diameter D1 and the outer diameter D2 of the circular fringe are determined.

Fine Wavelength Calculation

The fine. wavelength calculation is made using the course wavelength measured value and the measured values of D1 and D2.

The basic equation for wavelength is:

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$$\lambda = (2*n*d/m)\cos(R / f)\qquad\qquad(1)$$

where

λ is the wavelength, in picometers,

n is the internal index of refraction of the etalon, about 1.0003,

d is the etalon spacing, about 1542um for KrF lasers and about 934 μm for ArF lasers, controlled to +/-1um,

m is the order, the integral number of wavelengths at the fringe peak, about 12440,

R is the fringe radius, 130 to 280 PDA pixels, a pixel being 25 microns,

f is the focal distance from the lens to the PDA plane.

Expanding the cos term and discarding high order terms that are negligibly small yields:

$$\lambda = (2*n*d / m)\,[\,1 - (1/2)(R / f)^2\,]\qquad\qquad(2)$$

Restating the equation in terms of diameter D = 2*R yields:

$$\lambda = (2*n*d / m)\,[\,1 - (1/8)(D / f)^2\,]\qquad\qquad(3)$$

The wavemeter's principal task is to calculate λ from D. This requires knowing f, n, d and m. Since n and d are both intrinsic to the etalon we combine them into a single calibration constant named ND. We consider f to be another calibration constant named FD with units of pixels to match the units of D for a pure ratio. The integer order m varies depending on the wavelength and which fringe pair we choose. m is determined using the coarse fringe wavelength, which is sufficiently accurate for the purpose.

A couple of nice things about these equations is that all the big numbers are positive values. The WCM's microcontroller is capable of calculating this while maintaining nearly 32 bits of precision. We refer to the bracketed terms as FRAC.

$$FRAC = [\,1 - (1/8)(D / FD)^2\,]\qquad\qquad(4)$$

Internally FRAC is represented as an unsigned 32 bit value with its radix point to the left of the most significant bit. FRAC is always just slightly less than one, so we get maximal precision there. FRAC ranges from [1 - 120E-6] to [1 - 25E-6] for D range of { 560 ~ 260 } pixels.

When the ND calibration is entered, the wavemeter calculates an internal unsigned 64 bit value named 2ND = 2*ND with internal wavelength units of femtometers (fm) = 10^{-15}

meter = 0.001pm. Internally we represent the wavelength λ as FWL for the fine wavelength, also in fm units. Restating the equation in terms of these variables:

$$FWL = FRAC * 2ND/m \qquad\qquad (5)$$

The arithmetic handles the radix point shift in FRAC yielding FWL in fm. We solve for m by shuffling the equation and plugging in the known coarse wavelength named CWL, also in fm units:

$$m = \text{nearest integer}\,(\,FRAC * 2ND/CWL\,) \qquad\qquad (6)$$

Taking the nearest integer is equivalent to adding or subtracting FSRs in the old scheme until the nearest fine wavelength to the coarse wavelength was reached. Calculate wavelength by solving equation (4) then equation (6) then equation (5). We calculate WL separately for the inner and outer diameters. The average is the line center wavelength, the difference is the linewidth.

Bandwidth Calculation

The bandwidth of the laser is computed as $(\lambda_2 - \lambda_1)/2$. A fixed correction factor is applied to account for the intrinsic width of the etalon peak adding to the true laser bandwidth. Mathematically, a deconvolution algorithm is the formalism for removing the etalon intrinsic width from the measured width, but this would be far too computation-intensive, so a fixed correction $\Delta\lambda\epsilon$ is subtracted, which provides sufficient accuracy. Therefore, the bandwidth is:

$$\Delta\lambda = \left(\frac{D_2 - D_1}{2}\right) - \Delta\lambda\epsilon$$

$\Delta\lambda\epsilon$ depends on both the etalon specifications and the true laser bandwidth. It typically lies in the range of 0.1-1 pm for the application described here.

Better Bandwidth Measurements

The bandwidth value $\Delta\lambda$ as determined in the preceding section represent what is called the "full width half maximum" or FWHM bandwidth. It represents the width of the laser beam

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spectrum (i.e., intensity as a function of wavelength) at one half the maximum intensity. This is currently the bandwidth value which is typically monitored for lasers used for integrated circuit lithography. If the precise shape of the spectrum were known (for example, if it were known to be Gausian) these FWHM value could be used to determine the full spectrum the laser beam (i.e., the intensity of the laser beam at all wavelengths within the beam). However, in general the exact shape of the spectrum is not known with precision, so there is some uncertainty associated with using the FWHM values to represent the laser spectrum.

Another approach for monitoring the laser beams spectrum is to attempt to measure what is called the 95 Percent Integral (called the I-95). However, this also involves uncertainty because measurement of low intensity values in the "wings" of the spectrum are difficult to measure accurately because of instrument noise. Also, a good I95 measurement requires etalons with very high finess. These very high finess etalons are typically not robust enough for a production line laser.

Preferred alternative techniques make good use of the very fast dilectors and processors and storage bins described above. These techniques collection and analysis of large amounts of data and assume that the laser is operated in a burst mode, for example, bursts of 2000 pulses during a 0.2 second time period with the bursts separated by a down time of 0.2 second. Logic device such as PDA 402 stores all of the fringe data for each pulse in each burst in storage device 404 during the burst. Immediately after the burst is terminated (during the 0.2 second down time) processor 400 calculates the spectrum for each pulse and then calculates one or more average spectra values (e.g., eleven average values, i.e., the average of the first, second through ten percent of the pulses; plus the overall average spectrum). The algorithm for calculating the spectrum preferably should correct for various sources of noise especially in the wings of the spectrum and also subtract out any intensity contributions from adjacent fringes. The spectrum may be defined as an integral as a function of wavelength or it may be defined as a series of integrals such as: 10%I, 20%I, ... 90%I, or from the data the processor could be programmed to calculate and report more familiar spectral values such as FWHM and 95%I. The processor could be programmed to calculate report and/or store average values for each bursts and periodically report average values for selected window sizes during bursts.

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Enhanced Illumination

As repetition rates increase from the 4,000 Hz range to the range of 10,000 Hz, optical components in the wavemeter are exposed to greatly increased ultraviolet radiation. To counter this potential problem Applicants have made improvements to the wavemeter which reduces the per pulse exposure by up to a factor of 28. The details of these improvements are described in U.S. Patent Application entitled, "Gas Discharge Ultraviolet Waveleter with Enhanced Illumination," recently filed on June 14, 2002, which is incorporated by reference herein. FIG. 14I is a drawing of the modified wavelength with the enhanced illumination. The most important new features are a defractive diffuser 181D and a reduction telescope formed by lenses 181A and 181C which shrinks the beam cross section so that the two separate sample beams produced by reflections from both sides of beam splitter 170 are merged at the output surface of defractive diffuser 181D. Lens 181E images the output surface of defractive diffuser onto conventional diffuser 181G and only a tiny fraction of that merged an twice diffused beam is selected by slit 181H to be converted into spectral fringes by etalon 184 which in turn is imaged by lens 181L onto photodiode array 180. Beam splitter 181F splits the diffused beam from lens 181E into two parts, the first of which illuminates etalon 184 as described above and the second part is diffused by diffuser 181R and this twice diffused beams is used as a calibration beam for calibrating the wavemeter based on a metal vapor (platinum for ArF and iron for KrF) in vapor cell 198.

Feedback Control of Pulse Energy and Wavelength

Based on the measurement of pulse energy of each pulse as described above, the pulse energy of subsequent pulses are controlled to maintain desired pulse energies and also desired total integrated dose of a specified number of pulses all as described in U.S. Patent No. 6,005,879, Pulse Energy Control for Excimer Laser which is incorporated by reference herein.

Wavelength of the laser may be controlled in a feedback arrangement using measured values of wavelengths and techniques known in the prior art such as those techniques described in U.S. Patent No. 5,978,394, Wavelength System for an Excimer Laser also incorporated herein by reference. Applicants have recently developed techniques for wavelength tuning which utilize a piezoelectric driver to provide extremely fast movement of tuning mirror. Some of these techniques are described in United States Patent

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Application Serial No. 608,543, Bandwidth Control Technique for a Laser, filed June 30, 2000 which is incorporated herein by reference. FIGS. 16A and 16B are extracted from that application and show the principal elements of this technique. A piezoelectric stack is used for very fast mirror adjustment and larger slower adjustments are provided by a prior art stepper motor operating a lever arm. The piezoelectric stack adjusts the position of the fulcrum of the lever arm.

NEW LNP WITH COMBINATION PZT-STEPPER MOTOR DRIVEN TUNING MIRROR

Detail Design with Piezoelectric Drive

FIG. 16 is a block diagram showing features of the laser system which are important for controlling the wavelength and pulse energy of the output laser beam. Shown are a line narrowing module 15K which contains a three prism beam expander, a tuning mirror 14 and a grating. Wavemeter 104 monitors the output beam wavelength and provides a feedback signal to LNP processor 106 which controls the position of tuning mirror 14 by operation of a stepper motor and a PZT stack as described below. Operational wavelengths can be selected by laser controller 102. Pulse energy is also measured in wavemeter 104 which provides a signal used by controller 102 to control pulse energy in a feedback arrangement as described above. FIG. 16A is a block diagram showing PZT stack 80, stepper motor 82, mirror 14 and mirror mount 86.

FIG. 16B1 is a drawing showing detail features of a preferred embodiment of the present invention. Large changes in the position of mirror 14 are produced by stepper motor through a 26.5 to 1 lever arm 84. In this case a diamond pad 81 at the end of piezoelectric drive 80 is provided to contact spherical tooling ball at the fulcrum of lever arm 84. The contact between the top of lever arm 84 and mirror mount 86 is provided with a cylindrical dowel pin on the lever arm and four spherical ball bearings mounted (only two of which are shown) on the mirror mount as shown at 85. Piezoelectric drive 80 is mounted on the LNP frame with piezoelectric mount 80A and the stepper motor is mounted to the frame with stepper motor mount 82A. Mirror 14 is mounted in mirror mount 86 with a three point mount using three aluminum spheres, only one of which are shown in FIG. 16B1. Three springs 14A apply the compressive force to hold the mirror against the spheres.

FIG. 16B2 is a preferred embodiment slightly different from the one shown in FIG. 16B1. This embodiment includes a bellows 87 to isolate the piezoelectric drive from the environment inside the LNP. This isolation prevents UV damage to the piezoelectric element and avoid possible contamination caused by out-gassing from the piezoelectric materials. Also see FIG. 19D and the accompanying text below for an alternate LNP design providing greatly improved sealing of the LNP.

LNP Purge Techniques

It is known to purge line narrowing packages; however, the prior art teaches keeping the purge flow from flowing directly on the grating face so that purge flow is typically provided through a port located at positions such as behind the face of the grating. Applicants have discovered, however, that at very high repetition rates a layer of hot gas (nitrogen) develops on the face of the grating distorting the wavelength. This distortion can be corrected at least in part by the active wavelength control discussed above. Another approach is to purge the face of the grating as shown in FIG. 17. In FIG. 17, small holes (1 mm on ¼ inch spacings) in the top of 10-inch long 3/8 inch diameter purge tube 61 provides the purge flow. The purge gas can be nitrogen from a pure nitrogen supply as described in a following section. Also, in a preferred embodiment the LNP is purged with helium as described below. Other techniques are shown in FIGS. 17A, 17B and 17C.

Specific techniques useful for controlling wavelength and bandwidth are described in the following patent applications which are incorporated by reference herein U.S. Serial No. 09/794,782, filed February 27, 2001, entitled "Laser Wavelength Control With Piezoelectric Driver", U.S. Serial No.: 10/027,210, filed December 21, 2001, entitled "Laser Wavelength Control With Piezoelectric Driver" and U.S. Serial No.: 10/036,925, filed December 21, 2001, entitled "Laser Spectral Engineering For Lithographic Process".

Compensation for LNP Pressure Changes

At very high repetition rates and burst mode operation the LNP is subjected to substantial heating during wafer illumination periods and almost no heating during other periods. This can cause pressure changes in the LNP purge gas which can affect the wavelength.

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Applicants have determined that the wavelength changes about 1 pm for every 10 torr of pressure change. Variations in wavelength are typically corrected very quickly during laser operation with the wavelength feedback controls described above. However, there is not feedback when the laser is not operating and during the period immediately following high repetition operation is when the wavelength is changing most rapidly.

A preferred solution to this problem is to slightly pressurize the (such as will about 1 atm of gauge pressure) the LNP with purge gas to monitor the pressure and to correct for pressure changes during non-operation periods. FIG. 16F shows this is alone. Pressure of the LNP purge gas (N_2 in this case) is monitored by pressure gauge 200. During any period of more than a specified time such as 5 seconds when the laser has not fired, controller 202 directs tuning control 204 to adjust the position of PZT 80 and/or stepper motor 82 as shown in FIG. 16B2 in order to position tuning mirror 14 to compensate for the pressure change. The compensation is according to:

$$\Delta\lambda \text{ (pm)} = (P-P_0) \, a,$$

where:

P = pressure

P_0 = pressure prior to firing stops

a = pressure coefficient

= $\delta\lambda/\delta P$

= $\dfrac{\lambda\,(1-n)}{P_0} \approx 0.1$ pm/torr @ $\lambda = 248$nm

n = index of refraction of purge gas

= 1.0003 for nitrogen

This $\Delta\lambda$ is applied on top of (in addition to) any other appropriate turning during the off period to compensate, for example, for things such as thermal drift LNP components, or pre-drive instructions or open-loop wavelength changes.

LASER PURGE SYSTEM

This first embodiment of the present invention includes an ultra-pure N_2 purge system which provides greatly improved performance and substantially increases component lifetime.

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FIG. 19 is a block diagram showing important features of a first preferred embodiment the present invention. Five excimer laser components which are purged by nitrogen gas in this embodiment of the present system are LNP 2P, high voltage components 4P mounted on laser chamber 6P, high voltage cable 8P connecting the high voltage components 4P with upstream pulse power components 10P, output coupler 12P and wavemeter 14P. Each of the components 2P, 4P, 8P, 12P, and 14P are contained in sealed containers or chambers each having only two ports an N_2 inlet port and an N_2 outlet port. An N_2 source 16P which typically is a large N_2 tank (typically maintained at liquid nitrogen temperatures) at a integrated circuit fabrication plant but may be a relatively small bottle of N_2. N_2 source gas exits N_2 source 16P, passes into N_2 purge module 17P and through N_2 filter 18P to distribution panel 20P containing flow control valves for controlling the N_2 flow to the purged components. With respect to each component the purge flow is directed back to the module 17P to a flow monitor unit 22P where the flow returning from each of the purge units is monitored and in case the flow monitored is less than a predetermined value an alarm (not shown) is activated.

FIG. 19A is a line diagram showing specific components of this preferred embodiment including some additional N_2 features not specifically related to the purge features of the present invention.

N_2 Filter

An important feature of the present invention is the inclusion of N_2 filter 18. In the past, makers of excimer lasers for integrated circuit lithography have believed that a filter for N_2 purge gas was not necessary since N_2 gas specification for commercially available N_2 is almost always good enough so that gas meeting specifications is clean enough. Applicants have discovered, however, that occasionally the source gas may be out of specification or the N_2 lines leading to the purge system may contain contamination. Also lines can become contaminated during maintenance or operation procedures. Applicants have determined that the cost of the filter is very good insurance against an even low probability of contamination caused damage.

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A preferred N_2 filter is Model 500K Inert Gas Purifier available from Aeronex, Inc. with offices in San Diego, California. This filter removes H_2O, O_2, CO, CO_2, H_2 and non-methane hydrocarbons to sub-parts-per-billion levels. It removes 99.9999999 percent of all particulate 0.003 microns or larger.

Flow Monitors

A flow monitor in unit 22 is provided for each of the five purged components. These are commercially available units having an alarm feature for low flow.

Piping

Preferably all piping is comprised of stainless steel (316SST) with electro polished interior. Certain types of plastic tubing, comprised of PFA 400 or ultra-high purity Teflon, may be used.

Recirculation

A portion or all of the purge gas could be recirculated as shown in FIG. 19B. In this case, a blower and a water cooled heat exchanger is added to the purge module. For example, purge flow from the optical components could be recirculated and purge flow from the electrical components could be exhausted or a portion of the combined flow could be exhausted.

Helium Purge of LNP

In preferred embodiments the LNP is purged with helium and the remainder of the beam path is purged with nitrogen. Helium has a much lower index of refraction than nitrogen so thermal effects in the LNP are minimized with the use of helium. However, helium is about 1000 times more expensive than nitrogen.

Improved Seals

Applicants have discovered major advantages in providing an extremely "clean" beam path. Laser optics tend to deteriorate rapidly in the presence of high energy ultraviolet radiation combined with many forms of contamination including oxygen. Preferred techniques for enclosing the beam path are described in U.S. Patent Application Serial No. 10,000,991 filed November 14, 2001, entitled "Gas Discharge Laser With Improved Beam

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Path" which is incorporated by reference herein. FIGS. 19C, D, E and F are extracted from that application. FIG. 19C is a drawing showing bellows seals between the various components of gas discharge system similar to the master oscillator is described above. FIG. 19D shows a modification including a bellows arrangement to the LNP stepper motor to seal the interface between the motor and the LNP enclosure. FIG. 19E shows a thermally decoupled aperture for the LNP which minimizes heating in the LNP and also encloses the LNP entrance so that it can be purged with relatively inexpensive helium. Helium exits the LNP through a chamber window unit as shown at 95 in FIG. 19C. FIGS. 19F 1, 2, 3, 4 and 5 show easy sealing bellows seal used to provide seals between the laser modules but allowing quick easy decoupling of the modules to permit quick module replacement. FIG. 19G shows a special purge arrangement to purge the high intensity portion of a wavemeter. This special purge is described in a following section.

Advantages of the System

The system described herein represents a major improvement in long term excimer laser performance for KrF lasers and especially for ArF and F_2 lasers. Contamination problems are basically eliminated which has resulted in substantial increases in component lifetimes and beam quality. In addition, since leakage has been eliminated except through outlet ports the flow can be controlled to desired values which has the effect of reducing N_2 requirements by about 50 percent.

Sealed Shutter with Power Meter

This first preferred embodiment includes a sealed shutter unit 500 with a built in power meter as shown in FIGS. 20, 20A and 20B. With this important improvement, the shutter has two functions, first, as a shutter to block the laser beam and, second, as a full beam power meter for monitoring beam power whenever a measurement is needed.

FIG. 20 is a top view showing the main components of the shutter unit. These are shutter 502, beam dump 504 and power meter 506. The path of the laser output beam with the shutter in the closed position is shown at 510 in FIG. 20. The path with the beam open is shown at 512. The shutter active surface of beam stop element 516 is at 45° with the direction of the beam exiting the chamber and when the shutter is closed the beam is both absorbed in the shutter surface and reflected to beam dump 504. Both the beam dump

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active surface and the shutter active surface is chrome plated for high absorption of the laser beam. In this embodiment, beam stop element 516 is mounted on flexible spring steel arm 518. The shutter is opened by applying a current to coil 514 as shown in FIG. 20B which pulls flexible arm 518 and beam stop element 516 to the coil removing beam stop element 516 from the path of the output laser beam. The shutter is closed by stopping the current flow through coil 514 which permits permanent magnets 520 to pull beam stop element 516 and flexible arm 518 back into the close position. In a preferred embodiment the current flow is carefully tailored to produce an easy transmit of the element and arm between the open and close positions.

Power meter 506 is operated in a similar fashion to place pyroelectric photo detector in the path of the output laser beam as shown in FIGS. 20 and 20A. In this case, coil 520 and magnets 522 pull detector unit 524 and its flexible arm 526 into and out of the beam path for output power measurements. This power meter can operate with the shutter open and with the shutter closed. Current to the coil is as with the shutter controlled to provide easy transit of unit 524 into and out of the beam path.

<center>Improved WaveMeter Purge</center>

In this preferred embodiment a special N_2 purge technique is used to provide extra purging of the high ultraviolet flux portions of the wavemeter as well as the output coupler and the chamber output window block. This technique is shown in FIG. 22. As explained above the laser output beam intersects partially reflecting mirror 170 (see also FIG. 14) which passes 95% of the energy in the beam as an output beam. About 4% of the reflected beam is reflected from mirror 171 to energy detector 172 where the pulse energy is measured. (The other part of the reflected beam passes through mirror 171 as shown at 61A and goes to other monitors in the wave meter.) At 4,000 Hz this 5% of the output energy represents a lot of UV light so special care has been taken to assure that the gas in the path of this portion of the beam is very clean and pure. To do this the wavemeter is modified to seal the region between the upstream side of mirror 170, the upstream side of mirror 171 and the front side of the window of detector 172 from the rest of the wavemeter. And a special purge flow to and from this region is provided as shown at 62A. The remainder of the wavemeter is purged by a second purge flow shown at 64A.

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The purge flow 62A is confined in the wavemeter by seals at mirrors 170, 171 and the 172 detector window. The purge flow exits this region along the laser output beam path through a bellows region 6A back to the output coupler module 68A to purge it. The flow then flows through bellows unit 70A and into window block 72A, out through an exit port in the window block and an exit port in bellows unit 70A then back through a tube to N_2 purge module 17 as shown at 74A and in FIG. 19. The downstream side of window 170 is purged with purge flow from shutter module 5K. The purge flow may be from module 17 as shown in FIG. 19 or in some cases window 76A is removed and the output of shutter module is openly connected with a purged customer beam line in which case the exit purge line at 78A may be directed to a customer purge return system or exhausted to atmosphere.

OTHER HIGH REPETITION RATE IMPROVEMENTS

Constant Optical Parameters

High repetition rates as described herein may provide more illumination than is needed when the laser and other lithography equipment is new. As lithography lasers age optical beam quality characteristics can change. Usually, quality tends to deteriorate slowly. When the beam quality no longer meets specifications even after service, replacement of major components (such as the laser chamber, the LNP and/or the wavemeter) is normally necessary. Thus, over the life of the laser beam quality may vary substantially within specification ranges. This could be a problem for integrated circuit lithographers which utilize lithography equipment designed for optical quality laser beams. The result of "better" than normal laser quality could result in an undesirable variation in integrated circuit quality. One solution is to provide a laser system where beam quality remains substantially constant over laser life. This may be accomplished using techniques described in U.S. Patent Application Serial No. 10/036,727 filed December, 21, 2001 where the piezoelectric driver turning mirror can be used to provide wavelength stability values and bandwidth values corresponding to expected nominal values rather than the best values the laser is capable of. Pulse energy can also be controlled using the feedback controls described above to maintain energy stability values at an expected norm rather than the best possible. Fluorine concentration and laser gas pressure can also be regulated to produce expected beam quality values rather than the most stable values of pulse energy and wavelength and the narrowest possible bandwidth values.

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HIGH REP-RATE MOPA

In preferred embodiments of the present invention is applied in a master oscillator-power amplifier (MOPA) gas discharge laser system such as described in the following patent applications assigned to the assignee of this application: Serial No. 09/943,343, Serial No. 10/012,002, Serial No. 10,056,619 and Serial No. 10/141,216 all of which are incorporated by reference herein. FIG. 23 is a drawing of a MOPA system 4K being designed by Applicants and others. Beam quality is controlled in the master oscillator 8K and the pulse power is controlled in the power amplifier 10K. By increasing the pulse repetition rate the same UV energy can be provided with less energy per pulse. Reducing the per pulse energy results longer useful life of expensive lithography optical equipment. This embodiment as shown in FIG. 23 also include pulse stretching equipment (called pulse multiplier 12K) for the MOPA and a beam delivery unit 40A as discussed below.

Pulse Multiplier

Having energy to spare permits the addition of equipment to stretch the laser pulse duration. A technique for stretching the pulse duration is to split each pulse into two or more parts, delay all but the first part then join them back together. One such technique is described in U.S. Patent No. 6,067,311 which is assigned to Applicants' employer and is incorporated herein by reference. Another such technique is described in U.S. Patent Application Serial No. 10/006,913 filed November 29, 2001 which is incorporated by reference herein. FIGS. 24A, 24B and 24C drawings extracted from that application describes the technique. FIG. 24A and 24C show the before and after results of pulse stretching.

Various modifications may be made to the present invention without altering its scope. Those skilled in the art will recognize many other possible variations. The system could be designed for high pulse repetition rates other than Hz such as any repetition rate within the range of about 3000 Hz up to 6000 Hz to 10,000 Hz above. The laser system described above specifically for KrF could be utilized as an ArF laser by changing the gas mixture

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and modifying the LNP and wavemeter for 193nm operation. Preferably the electrode spacing is reduced from 16.5 mm to 13.5 mm. For example, active feedback control of bandwidth can be provided by adjusting the curvature of the line narrowing grating using a motor driver to adjust the bending mechanism shown in FIG. 22A. Or much faster control of bandwidth could be provided by using piezoelectric devices to control the curvature of the grating. Other heat exchanger designs should be obvious modifications to the configurations shown herein. For example, the four units could be combined into a single unit. There could be significant advantages to using much larger fins on the heat exchanger to moderate the effects of rapid changes in gas temperature which occurs as a result of burst mode operation of the laser. The reader should understand that at extremely high pulse rates the feedback control on pulse energy does not necessarily have to be fast enough to control the pulse energy of a particular pulse using the immediately preceding pulse. For example, control techniques could be provided where measured pulse energy for a particular pulse is used in the control of the second or third following pulse. Many variations and modifications in the algorithm for converting wavemeter etalon and grating data to wavelength values are possible. For example, Applicants have discovered that a very minor error results from a focusing error in the etalon optical system which causes the measured line width to be larger than it actually is. The error increases slightly as the diameter of the etalon fringe being measured gets larger. This can be corrected by scanning the laser and a range of wavelengths and watch for step changes as the measured fringes leave the windows. A correction factor can then be determined based on the position of the measured fringes within the windows. Accordingly, the above disclosure is not intended to be limiting and the scope of the invention should be determined by the appended claims and their legal equivalents.

CLAIMS

WE CLAIM:

1.   An extreme repetition rate gas discharge laser system capable of operating at pulse repetition rates in excess of 4,000 pulses per second, said laser comprising:

A)   a laser discharge chamber containing a laser gas and having two elongated electrodes, defining a discharge region,

B)   a blower system for producing sufficient gas velocities of said laser gas in said discharge region to clear from said discharge region, following each pulse, substantially all discharge produced ions prior to a next pulse when operating at a repetition rate in the range of 6,000 pulses per second or greater,

C)   a heat exchanger system capable of removing at least 16 kw of heat energy from said laser gas,

D)   a pulse power system configured to provide electrical pulses to said electrodes sufficient to produce laser pulses at rates of about 6,000 pulses per second with precisely controlled pulse energies in the range of about 5 mJ, and

E)   a laser beam measurement and control system capable of measuring pulse energy wavelength and bandwidth of energy pulses or substantially every pulse with feedback control of pulse energy and wavelength.

2.   A laser as in Claim 1 wherein said discharge laser system is a KrF, excimer laser system and the laser gas is comprised of krypton, fluorine and neon.

3.   A laser as in Claim 1 wherein said discharge laser system is a ArF, excimer laser system and the laser gas is comprised of argon, fluorine and neon.

4.   A laser as in Claim 1 wherein said discharge laser system is a F_2, comprised of fluorine and a buffer gas.

5.   A laser as in Claim 1 and wherein said chamber also comprises a vane structure upstream of said discharge region for normalizing gas velocity upstream of said discharge region.

6.   A laser as in Claim 1 where said fan comprises a shaft driven by two brushless DC motors.

7.   A laser as in Claim 6 wherein said motors are water-cooled motors.

8.   A laser as in Claim 6 wherein each of said motors comprise a stator and each of said motors comprise a magnetic rotor contained in a pressure cup separating a said stator from said laser gas.

9.   A laser as in Claim 6 wherein said tangential fan comprise a blade structure machined from said aluminum stock.

10.   A laser as in Claim 9 wherein said blade structure has an outside diameter of about five inches.

11.   A laser as in Claim 6 wherein said motors are sensorless motors and further comprising a master motor controller for controlling one of said motors and a slave motor controller for controlling the other motor.

12.   A laser as in Claim 1 wherein said finned heat exchanger system is water-cooled.

13.   A laser as in Claim 12 wherein said heat exchanger system comprises at least four separate water-cooled heat exchangers.

14.   A laser as in Claim 12 wherein heat exchanger system comprises at least one heat exchanger having a tubular water flow passage wherein at least one turbulator is located in said path.

15.   A laser as in Claim 13 wherein each of said four heat exchangers comprise a tubular water flow passage containing a turbulator.

16.   A laser as in Claim 1 wherein said pulse power power system comprise water-cooled electrical components.

17.   A laser as in Claim 16 wherein at least one of said water-cooled components is a component operated at high voltages in excess of 12,000 volts.

18.   A laser as in Claim 17 wherein said high voltage is isolated from ground using an inductor through which cooling water flows.

19.   A laser as in Claim 1 wherein said pulse power system comprises a resonant charging system to charge a charging capacitor to a precisely controlled voltage.

20.   A laser as in Claim 19 wherein said resonance charging system comprises a De-Qing circuit.

21.   A laser as in Claim 19 wherein said resonance charging system comprises a bleed circuit.

22.   A laser as in Claim 19 wherein said resonant charging system comprises a De-Qing circuit and a bleed circuit.

23.   A laser as in Claim 1 wherein said pulse power system comprises a charging system comprised of at least three power supplies arranged in parallel.

24.   A laser as in Claim 1 wherein said laser beam measurement and control system comprises an etalon unit, a photo diode array, a programmable logic device, and optics to focus laser light from said etalon unit on to said photo diode array wherein said programmable logic device is programmed to analyze data from said photodiode array to determine locations on said photo diode array of etalon fringes.

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25. A laser as in Claim 24 wherein said measurement an control system also comprises a microprocessor programmed to calculate wavelength and bandwidth from fringe data located by said programmable logic device.

26. A laser as in Claim 24 wherein said programmable logic device is programmed with an algorithm for calculating wavelength and bandwidth based on measurement of said fringes.

27. A laser as in Claim 26 wherein said programmable logic device is configured to make calculations of wavelength and bandwidth faster than 1/10,000 of a second.

28. A laser as in Claim 24 wherein said etalon unit comprises a defractive diffusing element.

29. A laser as in Claim 1 and further comprising a line narrowing unit comprising a tuning mirror driven at least in part by a PZT drive.

30. A laser as in Claim 29 wherein said tuning mirror is also driven in part by a stepper motor.

31. A laser as in Claim 29 and further comprising a pretuning means.

32. A laser as in Claim 29 and further comprising an active tuning means comprising a learning algorithm.

33. A laser as in Claim 29 and further comprising an adaptive feed forward algorithm.

34. A laser as in Claim 29 wherein said line narrowing unit comprises a grating defining a grating face and a purge means for forcing purge gas adjacent to said grating face.

35. A laser as in Claim 34 wherein said purge gas is nitrogen.

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36.   A laser as in Claim 34 wherein said purge gas is helium.

37.   A laser as in Claim 1 and further comprising a nitrogen purge system comprising a nitrogen purge system comprising a nitrogen filter.

38.   A laser as in Claim 1 and further comprising a nitrogen comprising a purge module comprising flow monitors said laser also comprising purge exhaust tubes for transporting exhaust purge gas from said laser.

39.   A laser as in Claim 1 and further comprising a shutter unit comprising an electrically operated shutter and a power meter which can be positioned in a laser output beam path with a command signal.

40.   A laser as in Claim 29 and further comprising a beam seal system providing a first beam seal between a first window of said chamber and line narrowing unit and a second beam seal between a second window of said chamber and an output coupler unit, each of said beam seals comprising a metal bellows.

41.   A laser as in Claim 40 wherein each of said first and second beam seals are configured to permit easy replacement of said laser chamber.

42.   A laser as in Claim 40 wherein each of said beam seals contain no elastomer, provide vibration isolation from said chamber, provide beam train isolation from atmospheric gases and permit unrestricted replacement of said laser chamber without disturbance of said LNP or said output coupler unit.

43.   A laser as in Claim 1 wherein said measurement and control system comprises a primary beam splitter for splitting off a small percentage of output pulses from said laser, a second beam splitter for directing a portion of said small percentage to said pulse energy detector and a means isolating a volume bounded said primary beam splitter, said secondary beam splitter and a window of said pulse energy detector from other portions of said measurement and control system to define an isolated region.

44.   A laser as in Claim 43 and further comprising a purge means for purging said isolated region with a purge gas.

45.   A laser as in Claim 44 wherein said laser further comprises an output coupler unit and an output window unit said purge means being configured so that exhaust from said isolated region also purges said output coupler unit and said output window unit.

46.   A laser as in Claim 1 wherein said chamber also comprises a current return having ribs with a generally rectangular cross section with a long direction in a direction of laser gas flow.

47.   A laser as in Claim 1 wherein said chamber comprises an anode and dielectric spacers positioned on two sides of said anode to improve laser gas flow in regions between the two electrodes.

48.   A laser as in Claim 1 wherein said pulse power system comprises a corona plate electrically connected to capacitors of a peaking capacitor bank and one of said electrodes by metal rods having lengths chosen to provide increased inductance.

49.   A laser as in Claim 1 wherein said discharge region defines an average width and said electrodes are configured limit said average width to less than 2 mm.

50.   A laser as in Claim 49 wherein each of said electrodes define a discharge surface and at least one of said electrode are comprised of a conductor having its discharge surface covered by insulator material with a plurality of discharge holes.

51.   A laser as in Claim 50 wherein said holes are approximately round with diameters in the range of 50 to 200 microns.

52.   A laser as in Claim 51 wherein said diameters are about 100 microns.

53.   A laser as in Claim 50 where both electrodes have their discharge surfaces covered with insulator material with a plurality of discharge holes.

54.   A laser as in Claim 50 wherein said insulator material is alumina.

55.   A laser as in Claim 1 wherein said heat exchanger system comprises at least one finned water-cooled heat exchanger having dual pass cooling water flow direction in each tube in the opposite direction as compared to the other tube.

56.   A laser as in Claim 1 wherein said heat exchanger system comprises at least one water-cooled finned heat exchanger and a water flow control system comprising a proportional valve and a fast acting digital on-off valve.

57.   A laser as in Claim 1 wherein said heat exchanger system comprises a monolithic heat exchanger created by machining cooling fins in a portion of said chamber.

58.   A laser as in Claim 57 wherein said monolithic heat exchanger comprises a plurality of cooling tubes in thermal contact with said cooling fins.

59.   A laser as in Claim 1 and further comprising a preionizer comprised of an elongated conductor integrated within a high voltage insulator, said conductor being positions in close proximity and parallel to one of said elongated electrodes.

60.   A laser as in Claim 1 and further comprising a suction means downstream of at least one of said elongated electrodes for improving laser gas flow in said discharge region.

61.   A laser as in Claim 1 and further comprising ceramic bearings supporting a shaft of said blower.

62.   A laser as in Claim 61 wherein said ceramic bearings comprise ceramic cages.

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63.   A laser as in Claim 61 wherein said ceramic bearings comprise a cageless race way, ceramic ball bearings and separation balls having smaller diameters than said ceramic ball bearings.

64.   A laser as in Claim 1 wherein said blower system comprises an injection circulator wherein a portion of laser gas flow in said chamber is extracted from said chamber pressurized and injected back into said chamber to produce a circulating laser gas flow.

65.   A laser as in Claim 1 wherein said blower system comprises a blower external to said laser discharge chamber.

66.   A laser as in Claim 65 wherein said heat exchanger system comprises a heat exchangers co-located with said blower.

67.   A laser as in Claim 65 wherein said heat exchanger system comprises a heat exchanger within said laser discharge chamber.

68.   A laser as in Claim 1 wherein said blower system comprises a blower driven by hydraulic turbine drive.

69.   A laser as in Claim 68 wherein said hydraulic turbine drive comprises a magnetic coupling, to couple hydraulic drive force into a shaft of a laser gas blower.

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FIG. 1 PRIOR ART
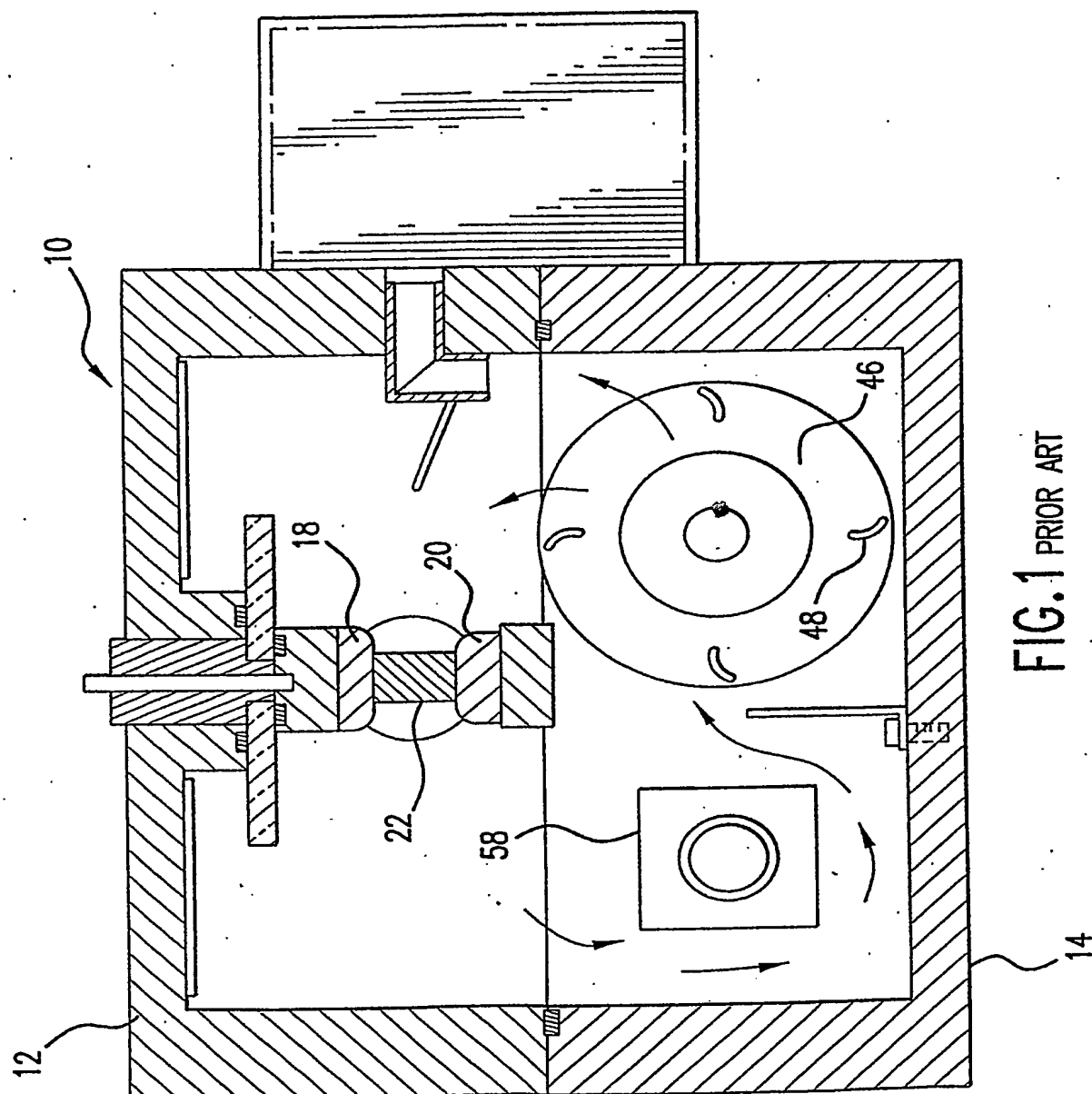
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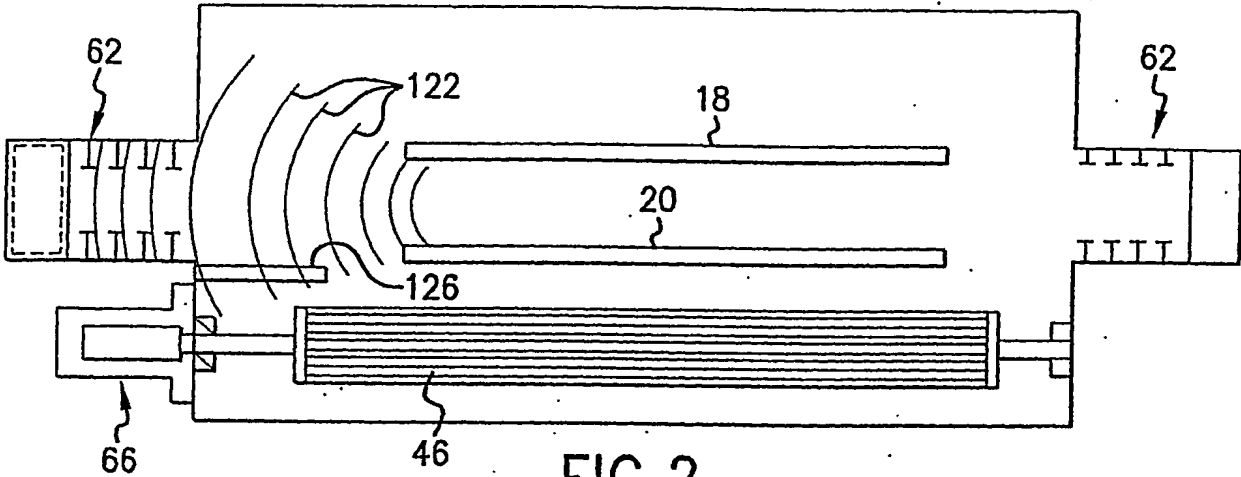
FIG.2
(PRIOR ART)

FIG.2A
(PRIOR ART)
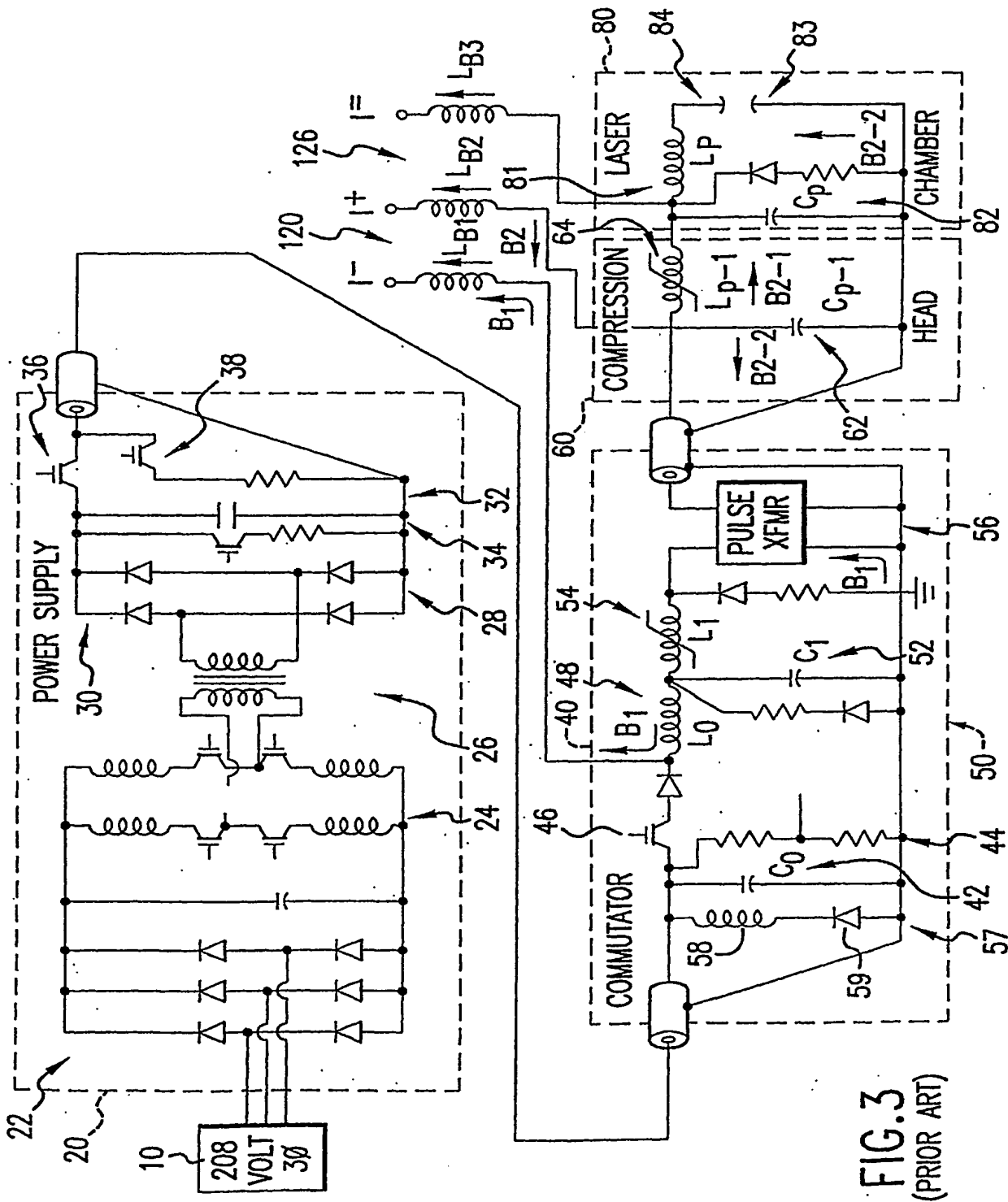
FIG.3
(PRIOR ART)

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FIG. 4A

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FIG.4B

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FIG.4D

FIG.4C

FIG.5

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FIG.6A

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FIG.6B

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FIG.7A

FIG.7

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FIG.8

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FIG.9A

FIG.9B

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FIG.10

FIG.10A

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FIG.11

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FIG.12

FIG.12A

FIG.12B

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FIG. 13

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FIG. 13A(1)

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FIG.13A(2)

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FIG.13A(3)

12B
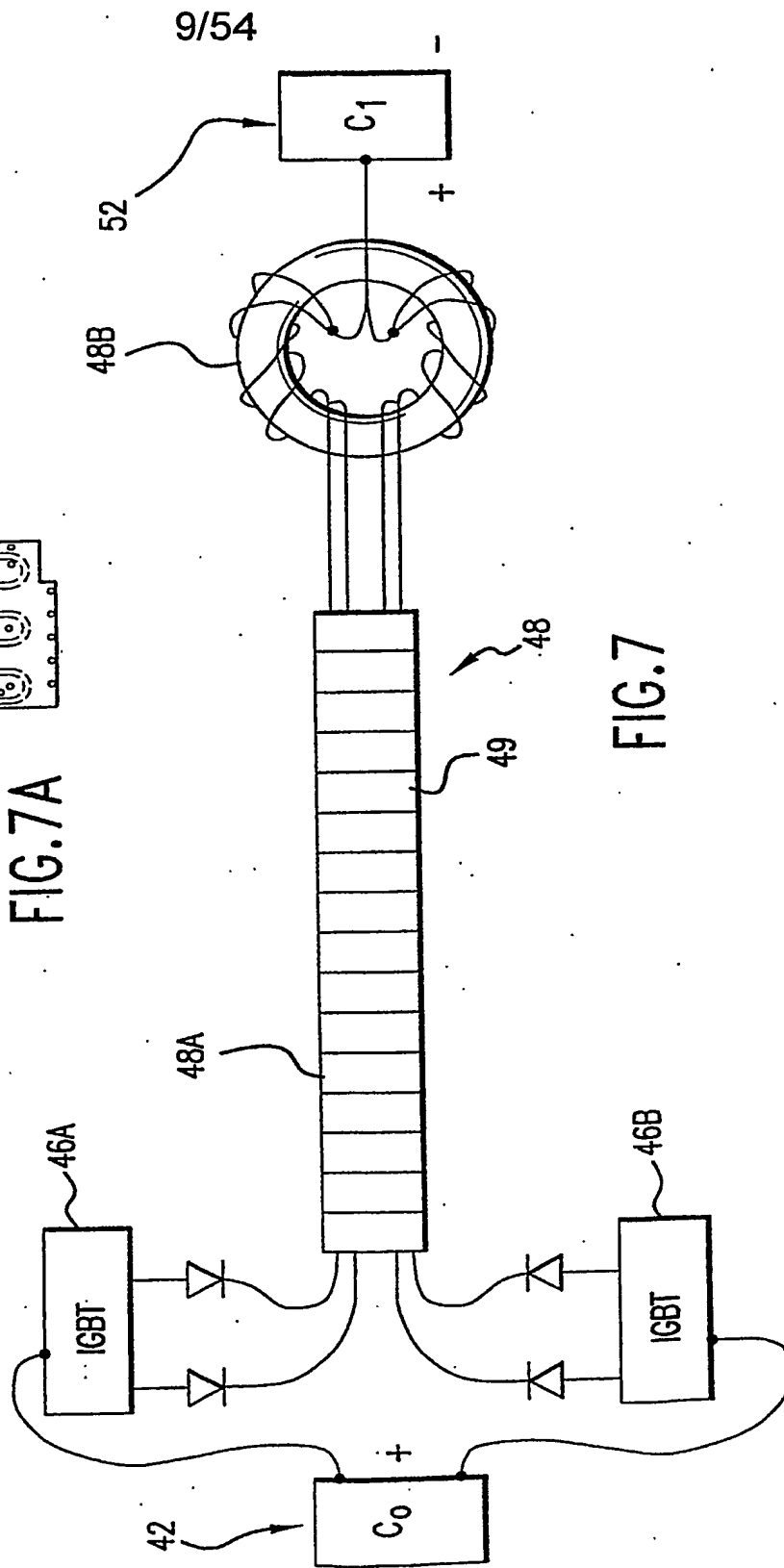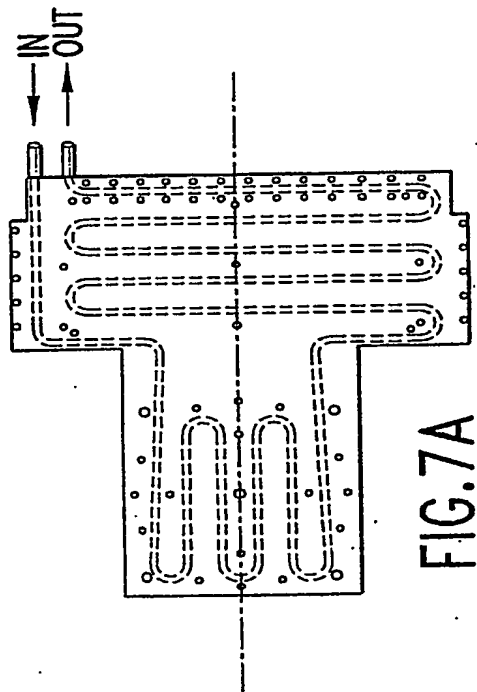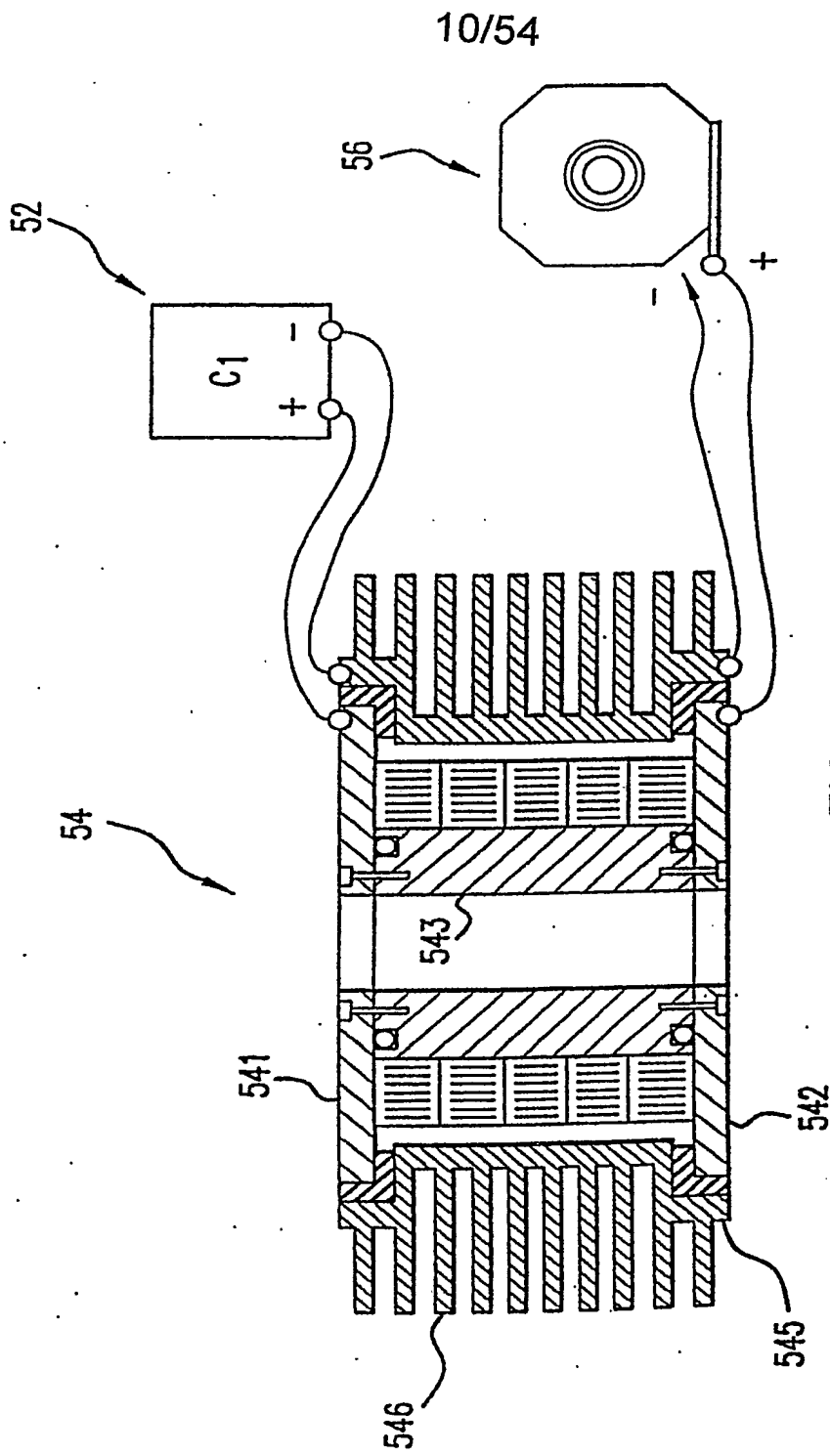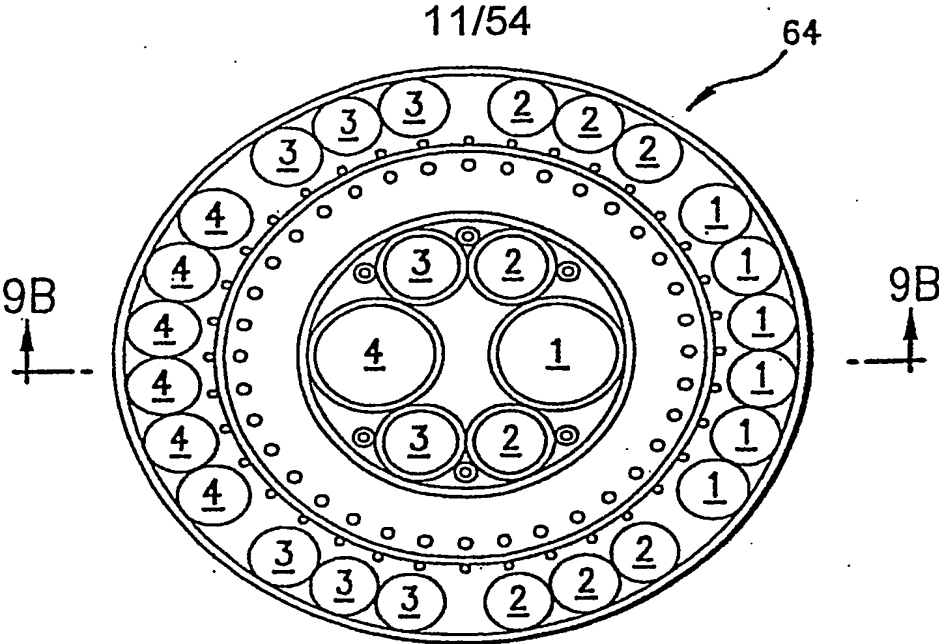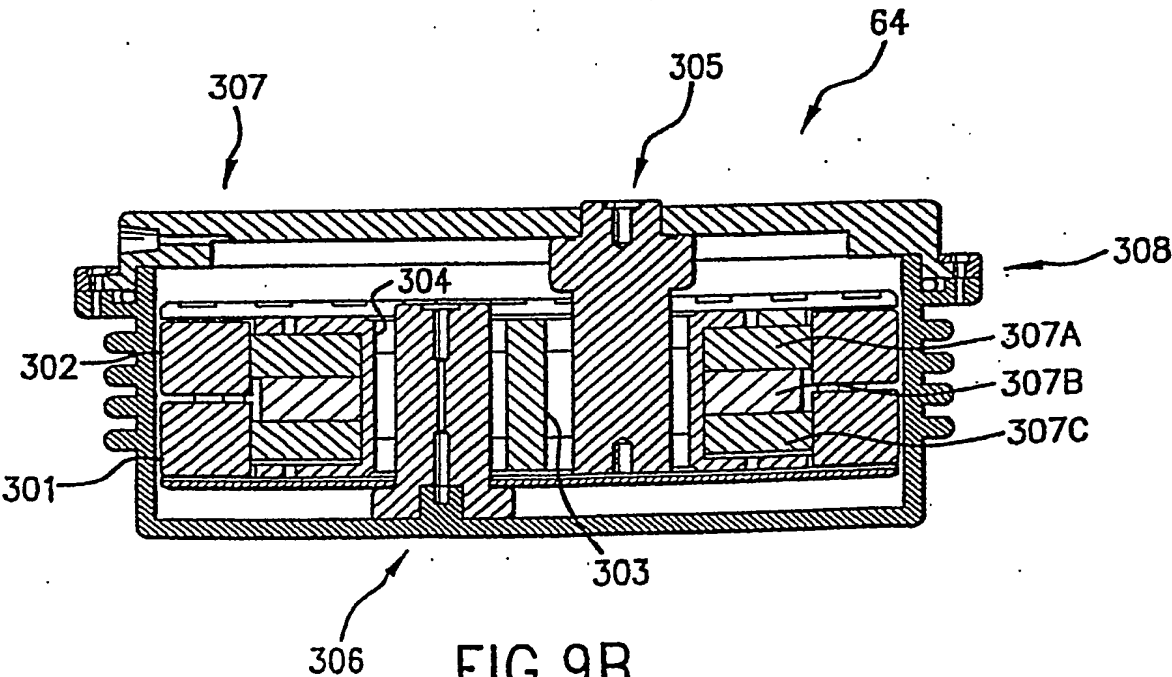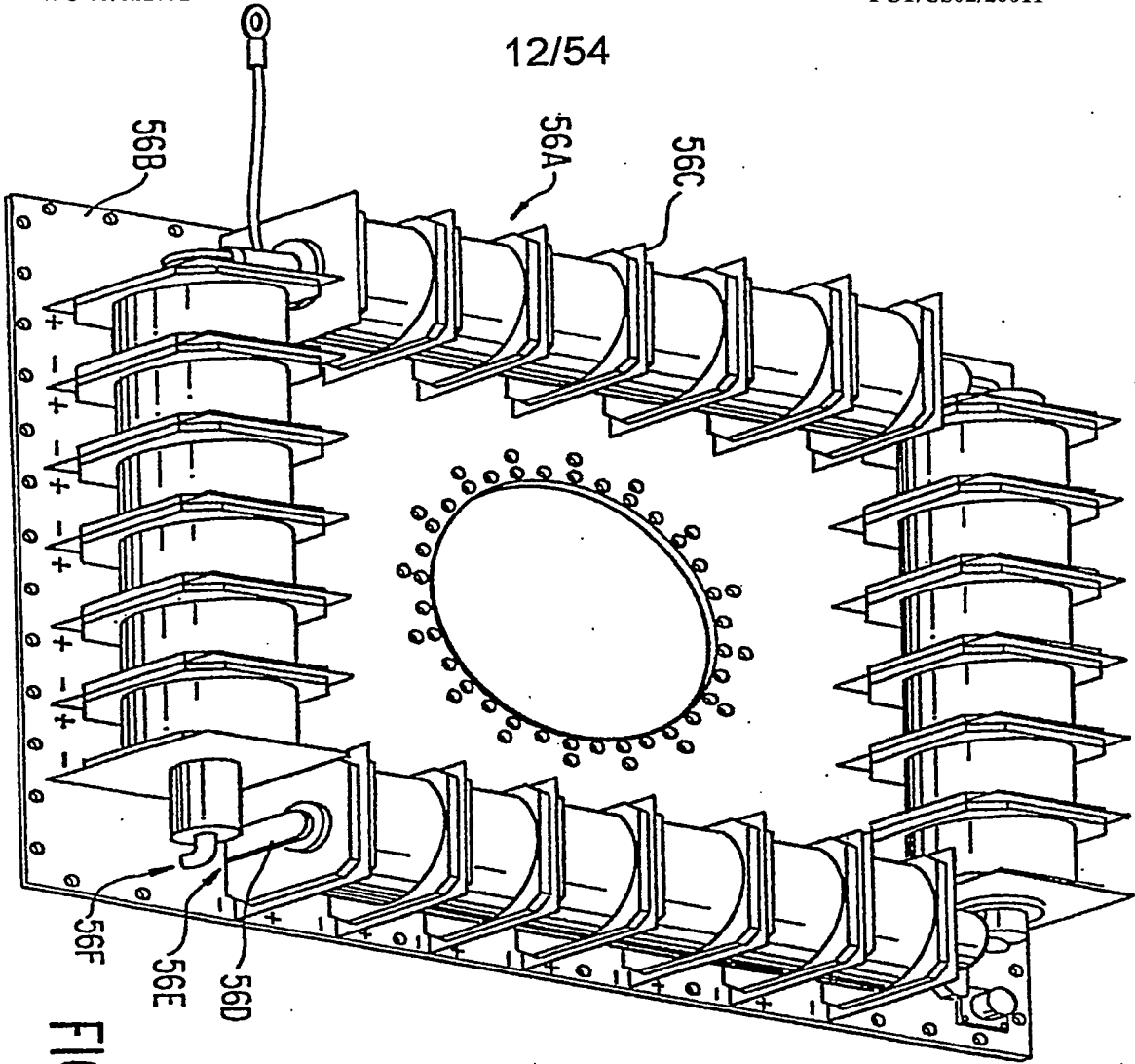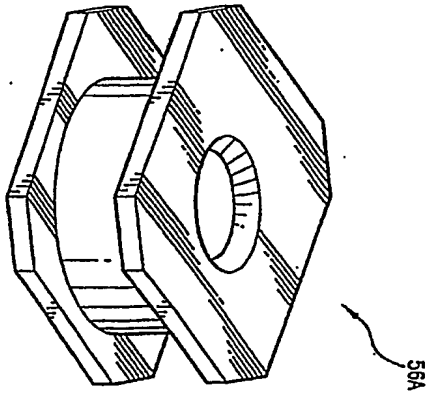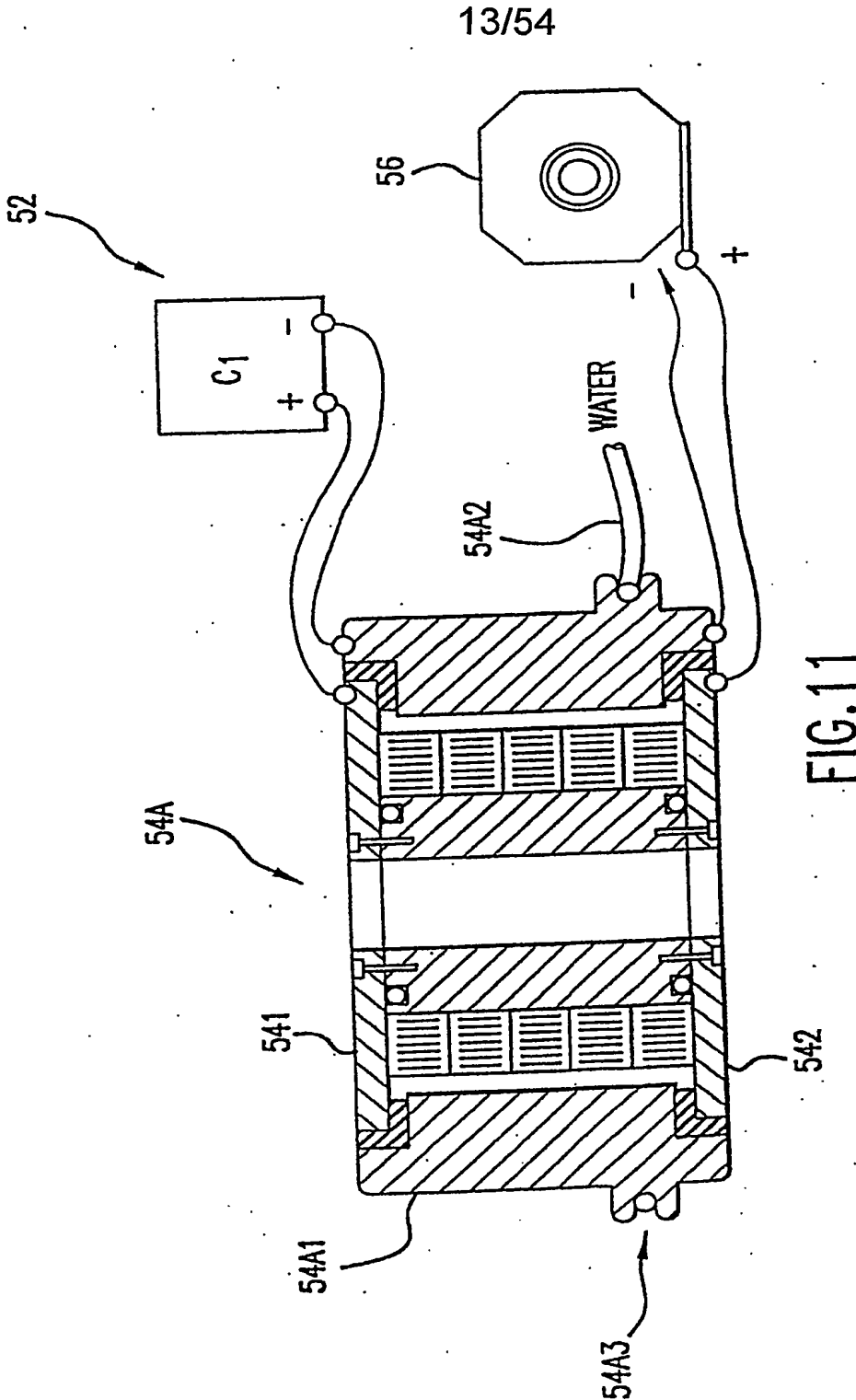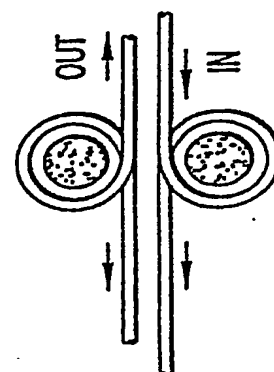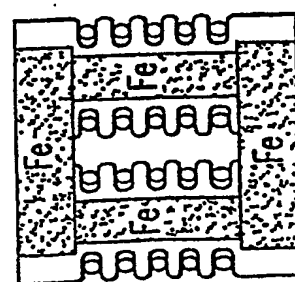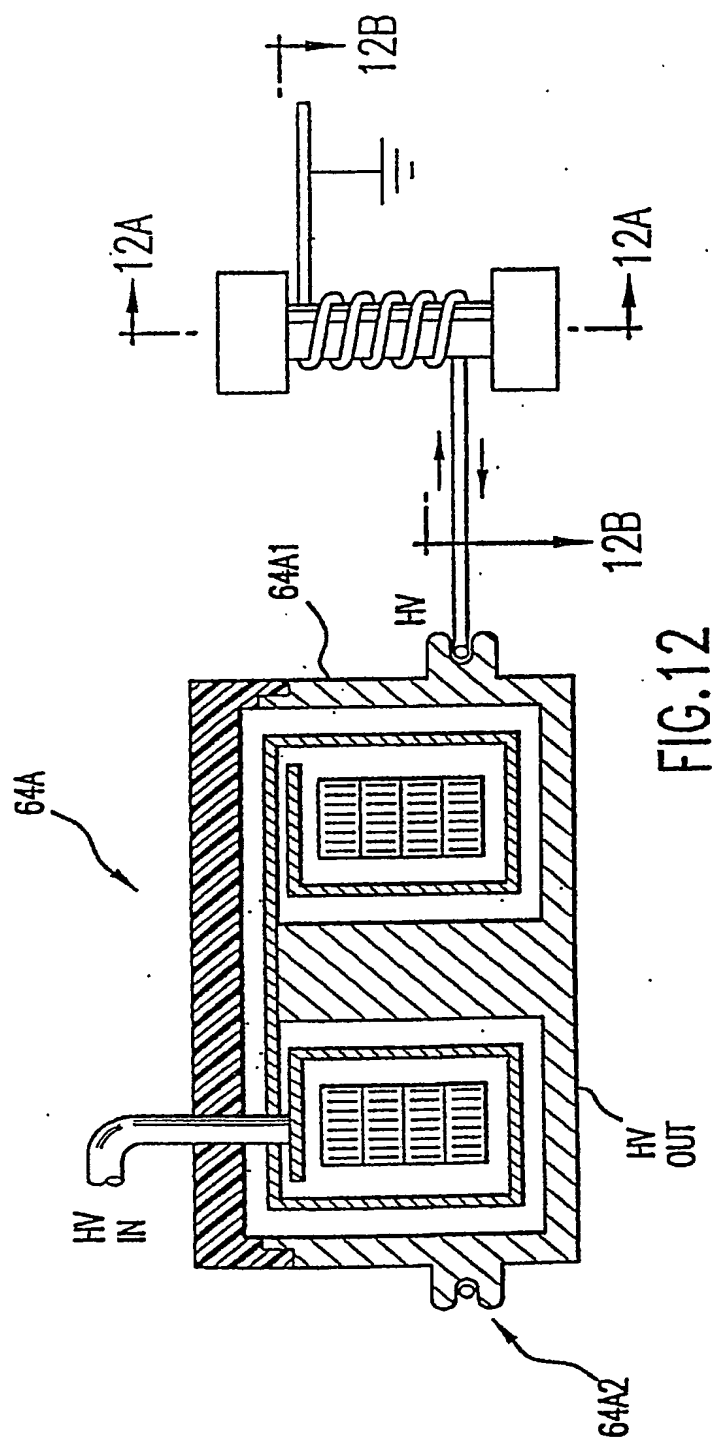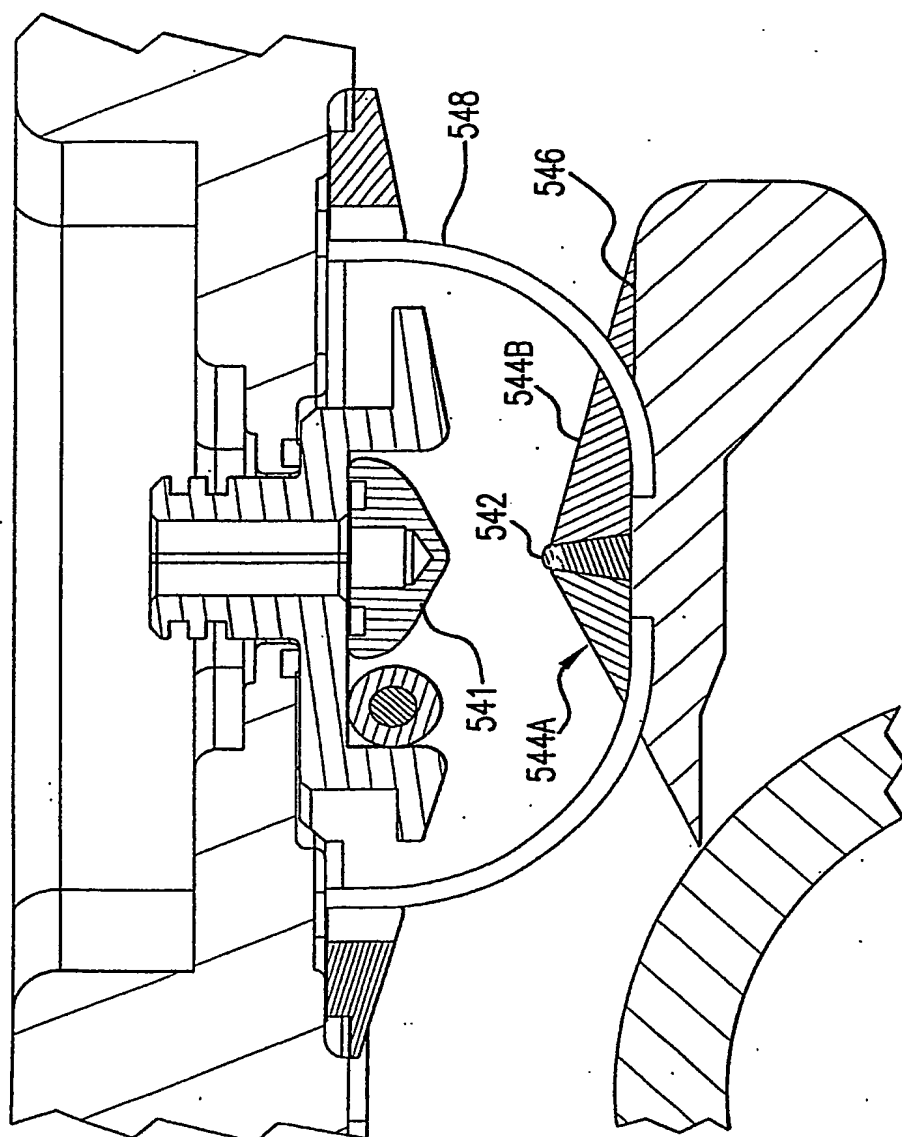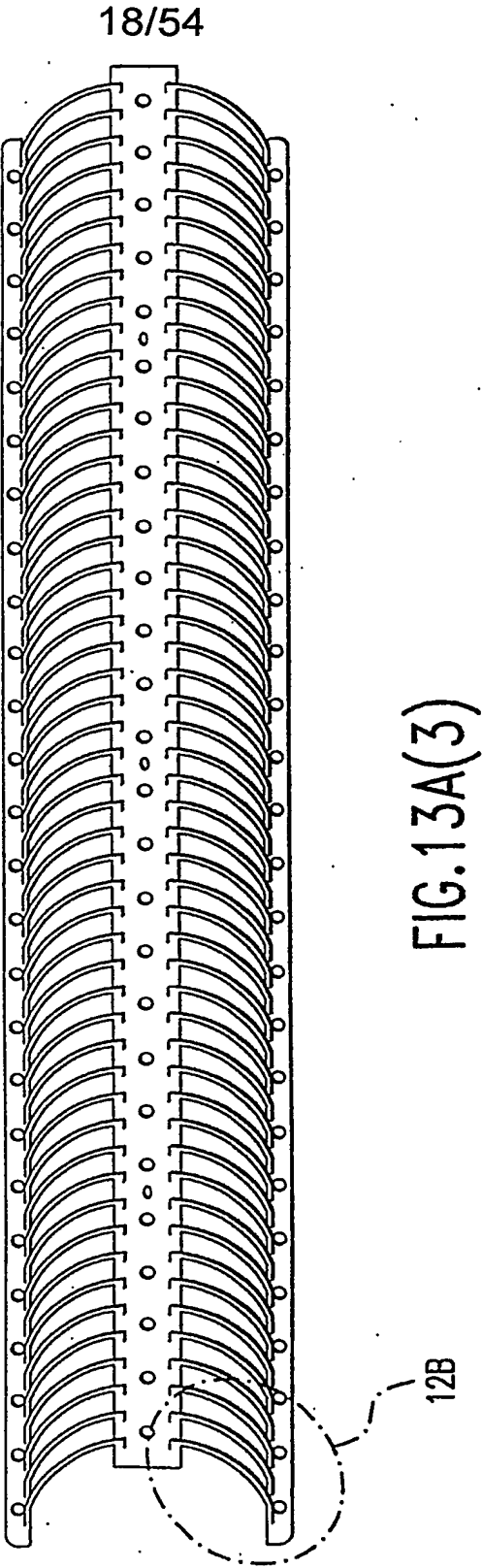
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FIG.13A(6)

FIG.13A(5)

FIG.13A(4)

12C

12D

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FIG.13A(8)

FIG.13A(7)

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FIG. 13B

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FIG. 13C

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FIG. 13D

FIG. 13E

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FIG. 13F

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FIG.14

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FIG.14A

FIG.14B

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FIG.14C

FIG.14D

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FIG. 14E

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FIG.15

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FIG.16

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MIRROR 14

MIRROR
MOUNT 86

PIEZO STACK

LEVER
ARM

84

FLOOR OF LNP   FLOOR OF LNP

STEPPER
MOTOR
MOUNT

82

STEPPER
MOTOR

LNP PROCESSOR

FROM WAVE METER

FIG.16A

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FIG. 16B1

STEPPER MOTOR

82A

82

14

86

85

84

81

80

PZT

80A

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CONTROLLER 202

200 P

LNP

TUNING CONTROL 204

FIG.16F

14A

14

85

87

PZT

84

STEPPER MOTOR

82

FIG. 16B2

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FIG.16C

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MEASURE λ_N

CALCULATE

$$\Delta\lambda E_4 = \frac{\sum\limits_{k=N-3}^{N} \lambda_k}{4} - \lambda_T$$

IS $[\Delta\lambda E_4] < 0.02PM$? — Y

N

CALCULATE

$$\Delta\lambda E_2 = \frac{\sum\limits_{k=N-1}^{N} \lambda_k}{2} - \lambda_T$$

IS $[\Delta\lambda E_2] < 0.02PM$? — Y

N

HAS 2ms ELAPSED SINCE T_o ? — Y — RECORD TIME T_o — SIGNAL LNP TO MOVE STACK ENOUGH TO PRODUCE $\Delta\lambda E_4$

N

HAS 1ms ELAPSED SINCE T_o ? — Y — RECORD TIME T_o — SIGNAL LNP TO MOVE STACK ENOUGH TO PRODUCE $\Delta\lambda E_2$

N

IS Sp<30% ? — MOVE STEPPER + STEP

IS Sp>70% ? — MOVE STEPPER − STEP

CALCULATE POSITION OF STACK 80 Sp

FIG.16D

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FIG.16E

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FIG.17

FIG.17A

FIG.17B

FIG.17C

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FIG. 18

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Right Side Ceramic Cage **540B**

Locking Pin **542**

Left Side Ceramic Cage **540A**

Ceramic Balls **541**

FIG. 18B

FIG.18A

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FIG.19

FIG.19B

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FIG.19A

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FIG.19C

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STEPPER MOTOR

FIG.19D

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FIG.19E

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FIG.19F2

FIG.19F4

FIG.19F1

FIG.19F3
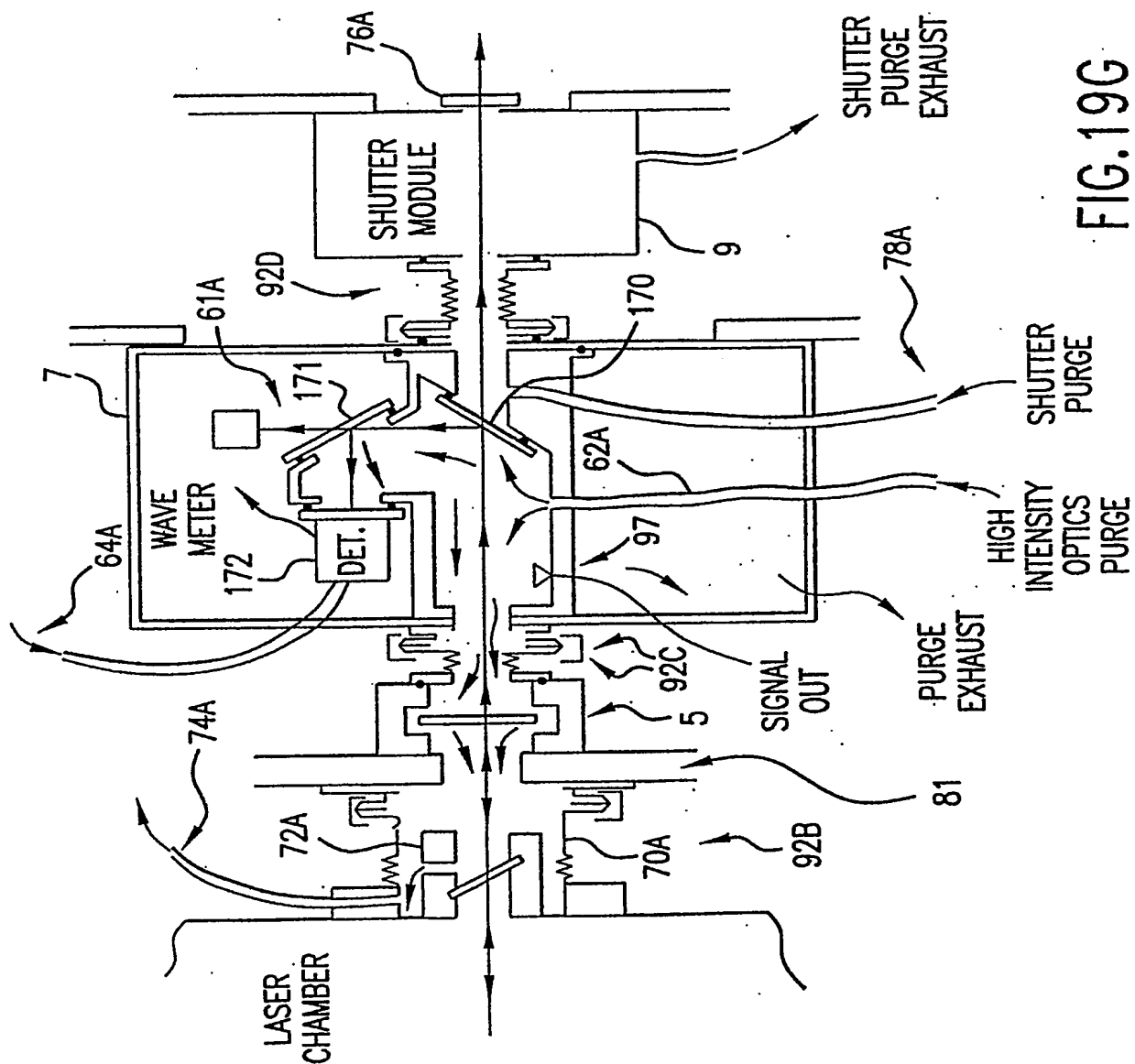
FIG.19F5

FIG.19G

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FIG.20

TOP VIEW

FIG.20A

FIG.20B

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FIG.21A

FIG.21

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FIG.21A

FIG.22

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FIG. 23

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FIG.24A

$T_{IS} = 18.16ns$

FIG.24B

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FIG.24C

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FIG. 25

FIG. 26
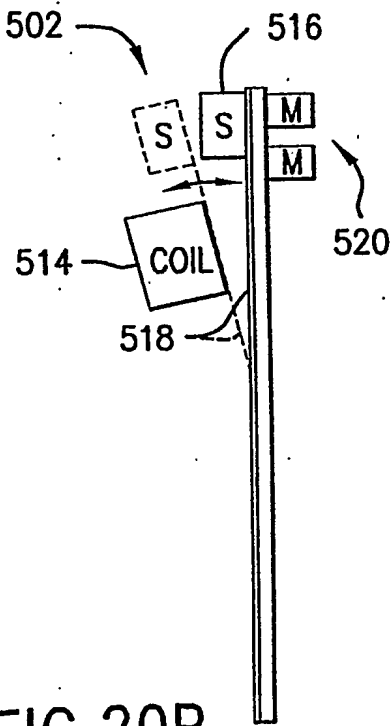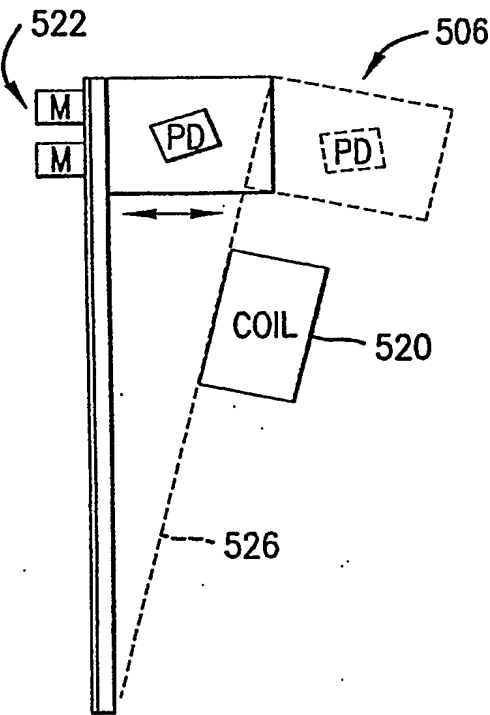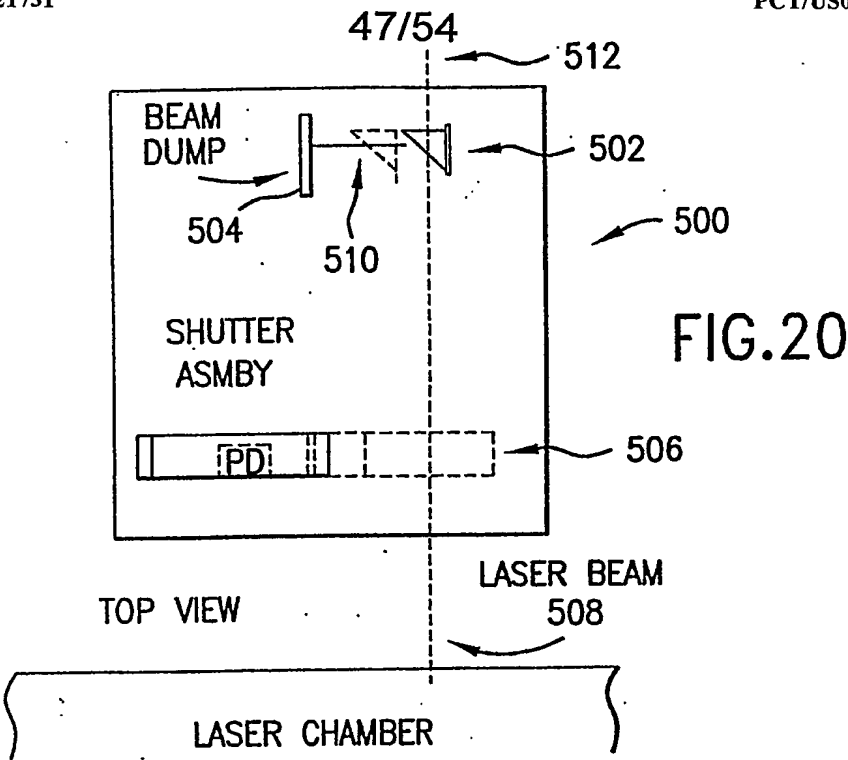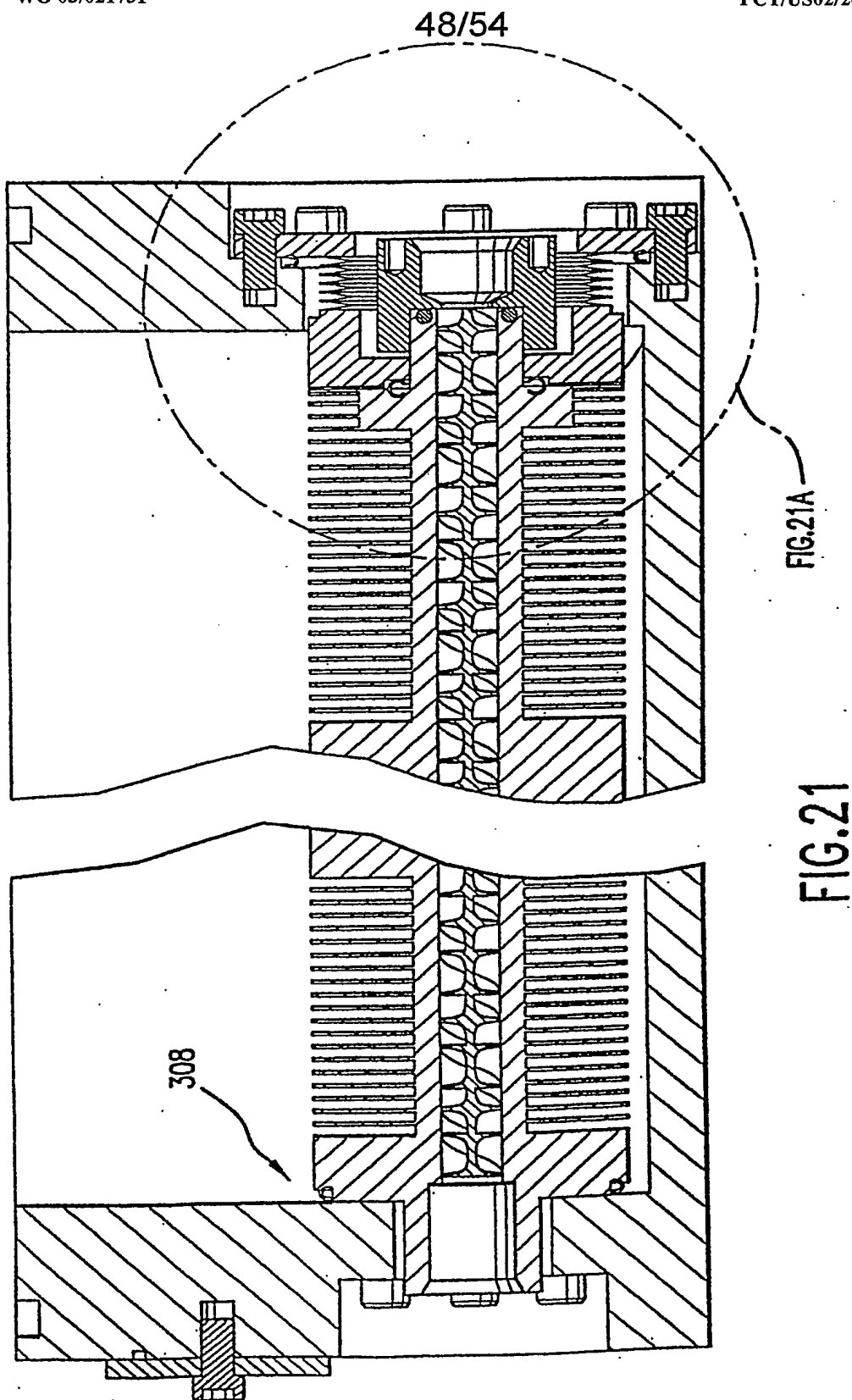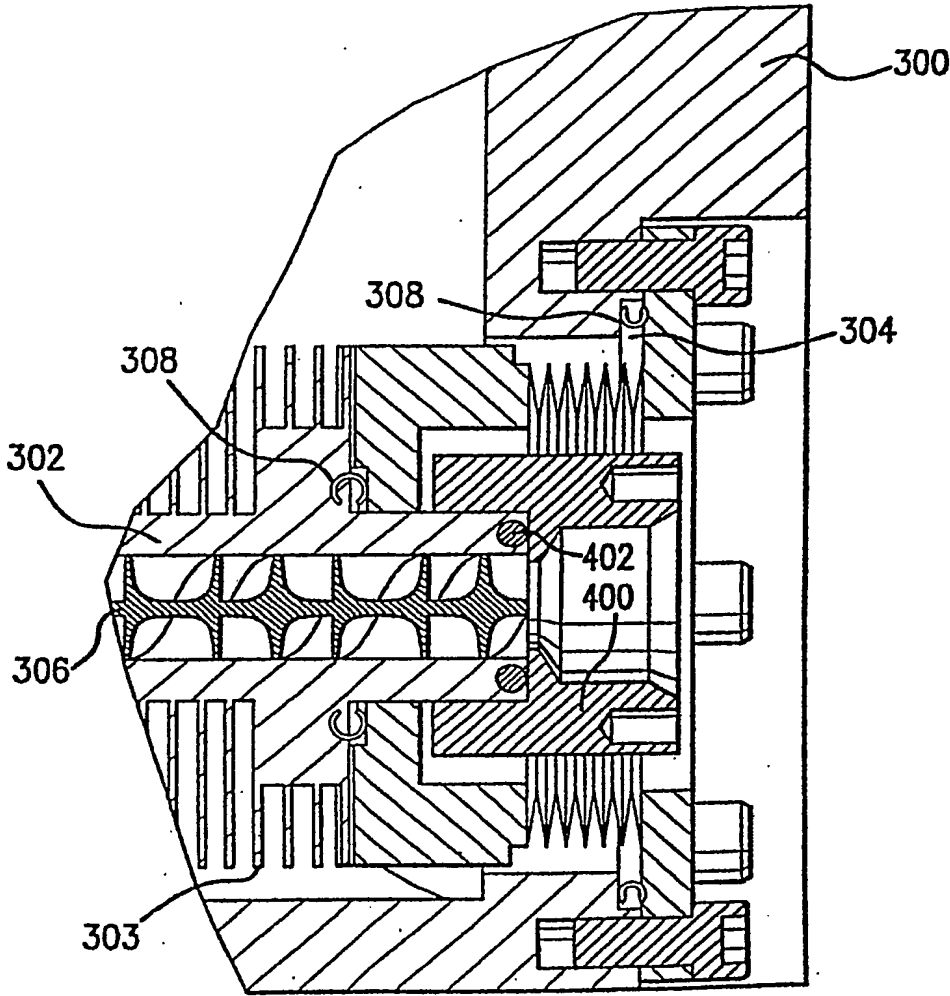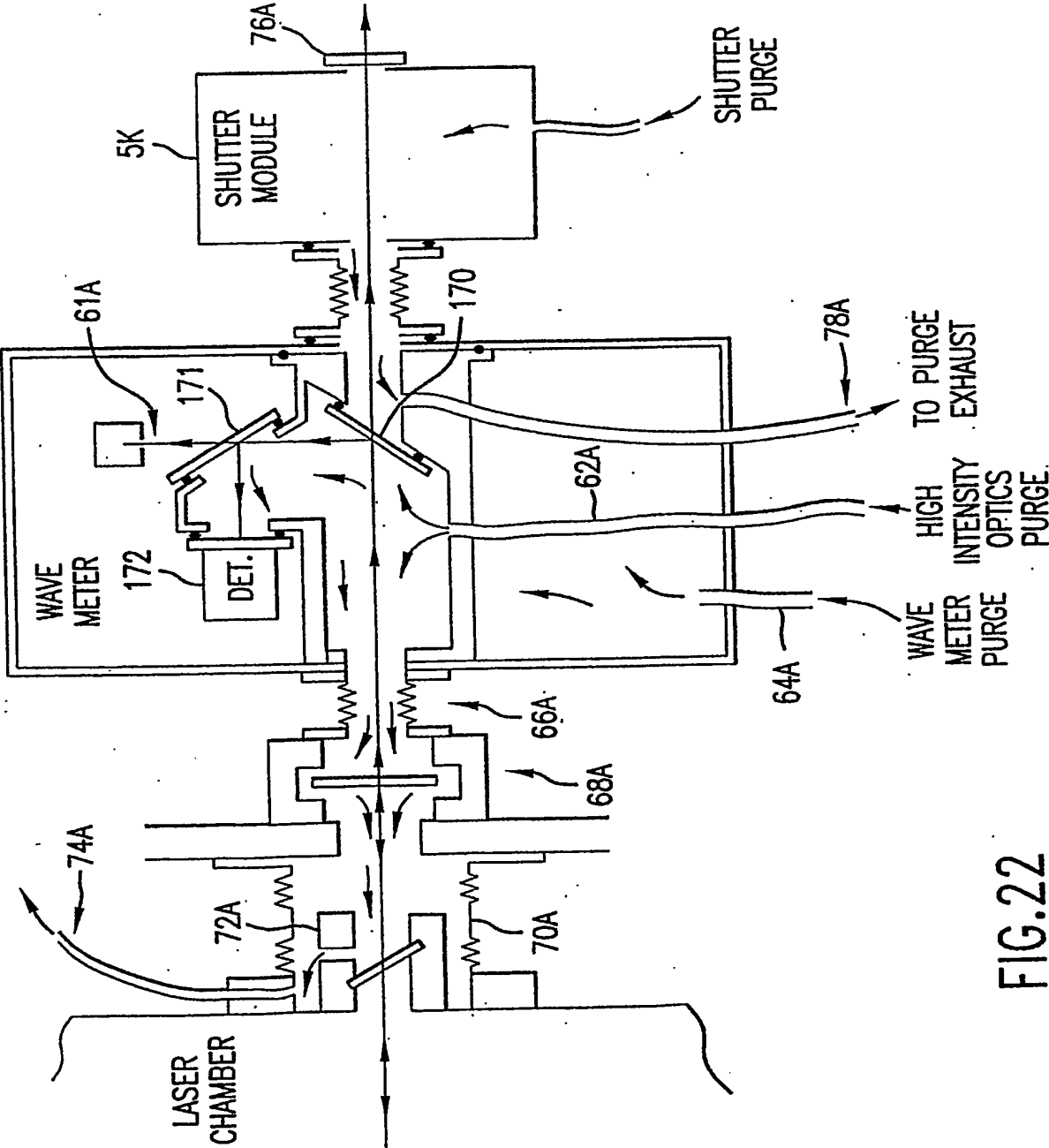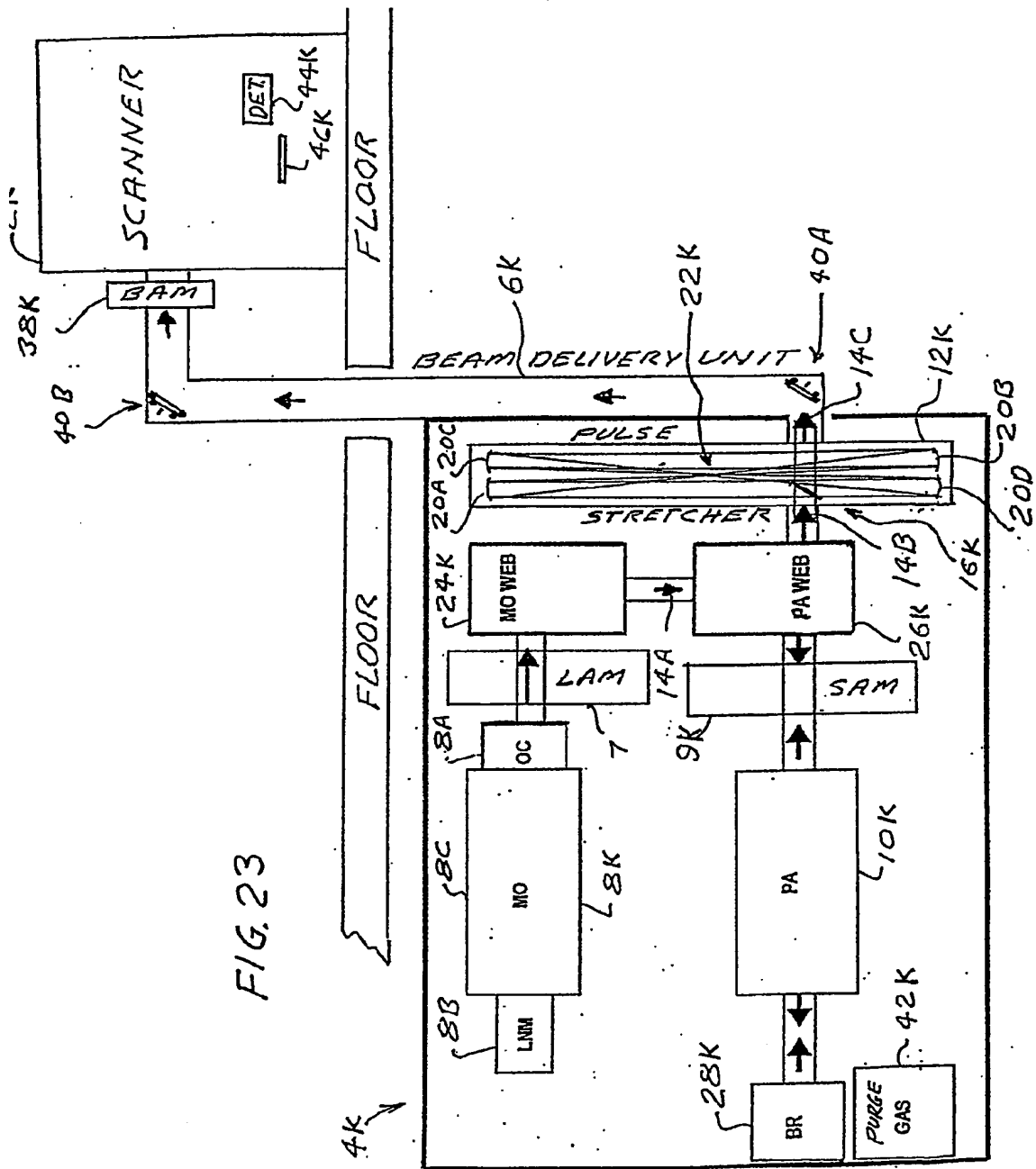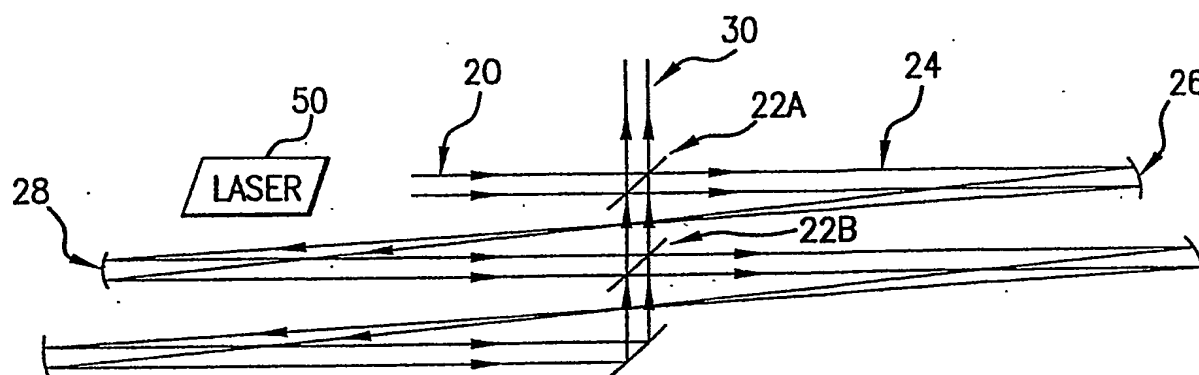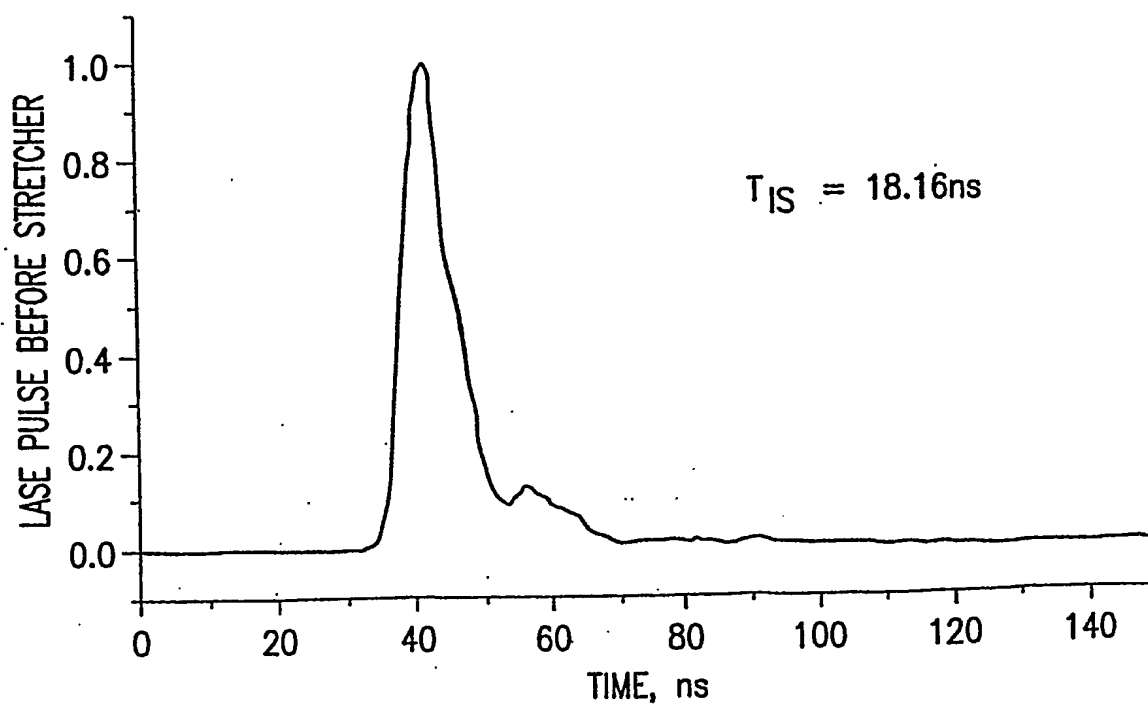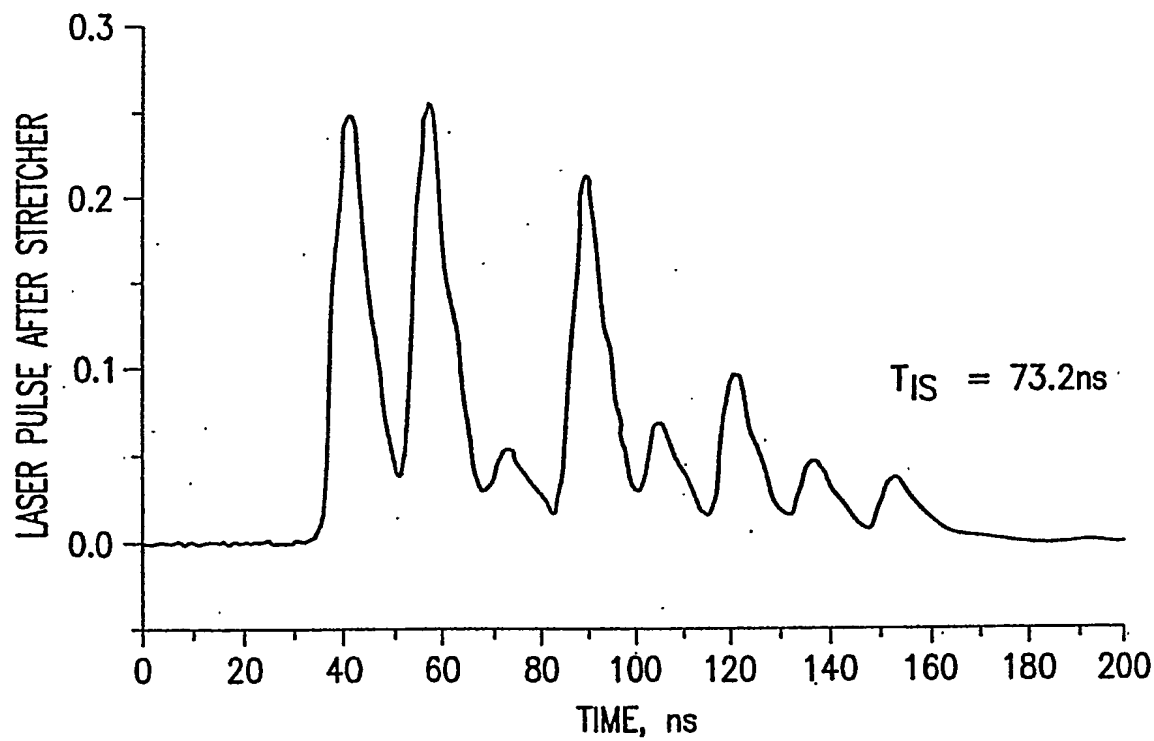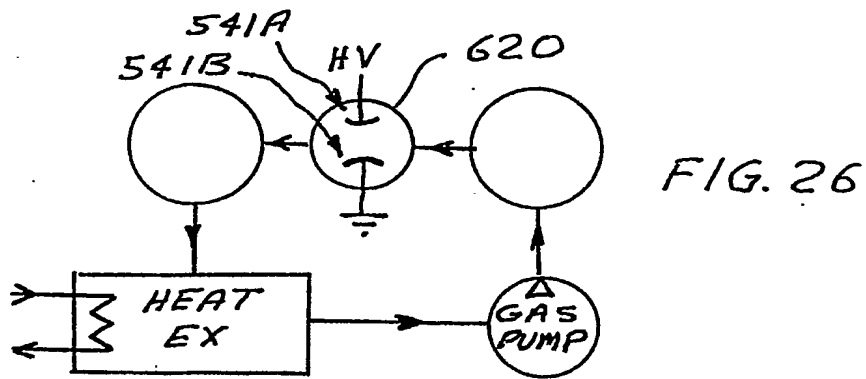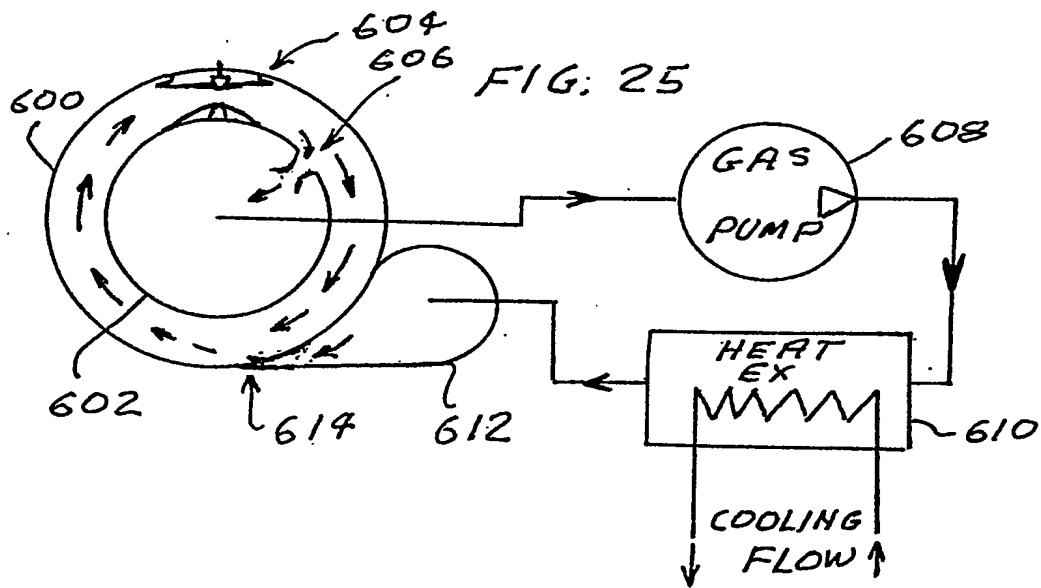
INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/26011

A.   CLASSIFICATION OF SUBJECT MATTER
IPC(7)   :   H01S 3/22
US CL   :   372/58
According to International Patent Classification (IPC) or to both national classification and IPC

B.   FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
    U.S. : 372/58

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
USPOT, USPBPUB, EPO, JPO ABSTRACT, DERWENT, IBMTDB

C.   DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,455,658 A (Sutter) 19 June 1984 (19.06.1984) entire doc.	1-69
A	US 5,189,678 A (Ball) 23 February 1993 (23.02.1993) entire doc.	1-69
A	US 4,223,279 A (Bradford) 16 September 1980 (16.09.1980) entire doc.	1-69

☐   Further documents are listed in the continuation of Box C.   ☐   See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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Date of the actual completion of the international search	Date of mailing of the international search report
23 September 2002 (23.09.2002)	0 5 NOV 2002

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